

**Improving Thermal Performance of Energy Active Window
Systems by Integrating Air Flow Elements to Enhance
Occupants' Comfort in Hot Climates**

BY

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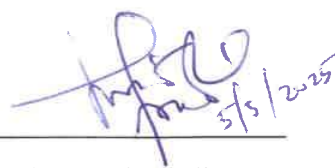
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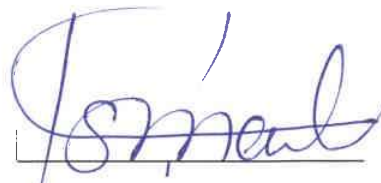
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Dedication

[This Thesis is dedicated to my Parents & Family]

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LIST OF ABBREVIATIONS AND SYMBOLS

ASHRAE	American Society of Heating, Ventilation & Air Conditioning Engineering
CFD	Computational Fluid Dynamics
CIBSE	Chartered Institution of Building Services Engineers
EAW	Energy Active Window
SAW	Supply Air Window
DAW	Dual Airflow Window
ExAW	Exhaust Air Window
EAWo	Energy-active window base case
EAWb	Energy-active window best case (square bars-alternative 2)
IF	Inflow
OF	Outflow
Og	Outer glazing
Ig	Inner glazing
ISO	International Organization for Standardization
Nu	Nusselt Number

k_{glass}	Thermal conductivity of the glass pane (W/(m·K))
k_{air}	Thermal conductivity of air in the gap (W/(m·K))
h_{inner}	Convective heat transfer coefficient on the inner glass surface (W/(m ² ·K))
h_{outer}	Convective heat transfer coefficient on the outer glass surface (W/(m ² ·K))
A	Surface area of the glass pane perpendicular to heat flow (m ²)
T_{s1}	Temperature of the inner glass surface (K)
T_{s2}	Temperature of the outer glass surface (K)
$T_{\infty 1}$	Indoor air temperature (K)
$T_{\infty 2}$	Outdoor air temperature (K)
ϵ_{glass}	Emissivity of the glass surfaces
d_{glass}	Thickness of each glass pane (m)
d_{gap}	Thickness of the air gap between the glass panes (m)
ρ	Density of the fluid
$\mathbf{v}$	Velocity Vector
t	Time
$\nabla \cdot$	Divergence Operator
p	Pressure

τ	Viscous Stress Tensor
$\mathbf{f}$	Body Force Per Unit Volume
c_p	Specific Heat at Constant Pressure
T	Temperature
Φ	Any Viscous Heating Term
$\dot{q}$	Volumetric Heat Source or Sink

]

ABSTRACT

Full Name : Syed Yaqeen Mahdi

Thesis Title : Improving Thermal Performance of EAW Systems by Integrating Air Flow Elements to Enhance Occupants' Comfort in Hot Climates.

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This study presents a comprehensive numerical investigation into the thermal performance enhancement of an Energy-Active Window (EAW) system through internal airflow integration and geometric optimization. The baseline model of EAW, a double and triple-glazed configuration with passive air channels, was compared against multiple design alternatives incorporating circular, triangular, and square polycarbonate bars placed at various intervals within the airflow slots to enhance air mixing and heat transfer. Using CFD simulations in ANSYS Fluent, airflow behaviour and heat transfer patterns were evaluated across a velocity range of 0.24 m/s to 0.57 m/s while corresponding performance metrics such as outflow air temperature, inner glazing temperature and average of pane temperature differences (ΔT_{avg}) were systematically recorded.

Among all the tested configurations, Square Bar Alternative 2 (SA2) emerged as the optimal design with three bars spaced at 0.05 m c/c in the outflow air slot. This best-case configuration demonstrated a **0.65°C** increase in outflow air temperature and a **2.45°C**

reduction in inner glazing temperature compared to the base EAW model at 0.24 m/s velocity, confirming superior thermal insulation and heat recovery. Moreover, bar spacing significantly influences heat transfer, with tighter spacing increasing performance by enhancing residence time and surface interaction.

Further, annual simulations performed in EnergyPlus (via DesignBuilder) revealed that the best-case EAW reduced cooling energy consumption by up to **25%** compared to a double-glazed system, 18% compared to a triple-glazed system, and **5%** compared to the EAW base model. The thermal comfort analysis using Fanger PMV values also showed that the best case consistently maintained PMV between -0.68 and 0.98, keeping occupants within or very close to the neutral thermal comfort range year-round. At the same time, conventional double and triple-glazed systems fluctuated further outside this range.

The EAW best-case (SA2 with bar spacing of 0.05 m c/c) U-value was calculated to be 0.12 W/m².K, significantly outperforming conventional glazing values (ranging from 2.2 to 5.8 W/m².K). These results highlight the potential of geometrically optimized EAW systems to reduce energy loads while significantly improving indoor comfort. The proposed design offers a practical, passive, and scalable solution for next-generation energy-efficient building envelopes.

ملخص الرسالة

الاسم الكامل:

عنوان الرسالة:

التخصص:

تاريخ الدرجة العلمية:

من خلال تكامل تدفق (EAW) تقدم هذه الدراسة تحقيقاً رقمياً شاملاً في تحسين الأداء الحراري لنظام نافذة الطاقة النشطة ، وهو تكوين زجاجي مزدوج وثلاثي مع قنوات EAW الهواء الداخلي والتحسين الهندسي. تمت مقارنة النموذج الأساسي لـ هواء سلبية، مع بدائل تصميم متعددة تتضمن قضبان بولي كربونات دائرية ومثلثة ومربعة موضوعة على فترات مختلفة داخل ، تم ANSYS Fluent فتحات تدفق الهواء لتحسين خلط الهواء ونقل الحرارة. باستخدام محاكاة ديناميكا الموائع الحسابية في تقييم سلوك تدفق الهواء وأنماط نقل الحرارة عبر نطاق سرعة يتراوح من 0.24 م/ث إلى 0.57 م/ث بينما تم تسجيل مقاييس (ΔT_{avg}) الأداء المقابلة مثل درجة حرارة الهواء الخارج ودرجة حرارة الزجاج الداخلي ومتوسط فروق درجة حرارة الألواح بشكل منهجي.

، مع ثلاثة قضبان متباعدة بمقدار 0.05 م/ث في (SA2) من بين جميع التكوينات المختبرة، ظهر البديل 2 للقضيب المربع فتحة تدفق الهواء الخارجي، باعتباره التصميم الأمثل. أظهر هذا التكوين الأمثل زيادة قدرها 0.65 درجة مئوية في درجة الأساسي EAW حرارة الهواء الخارج وانخفاضاً قدره 2.45 درجة مئوية في درجة حرارة الزجاج الداخلي مقارنةً بنموذج بسرعة 0.24 متر/ثانية، مما يؤكد العزل الحراري واستعادة الحرارة بشكل أفضل. علاوة على ذلك، وُجد أن تباعد القضبان يؤثر بشكل كبير على انتقال الحرارة، حيث يؤدي التباعد الضيق إلى زيادة الأداء من خلال تحسين وقت الإقامة والتفاعل السطحي

أن أفضل (DesignBuilder عبر) EnergyPlus وعلاوة على ذلك، كشفت عمليات المحاكاة السنوية التي أجريت في قللت من استهلاك طاقة التبريد بنسبة تصل إلى 24.6٪ مقارنةً بنظام الزجاج المزدوج، و17.6٪ مقارنةً بنظام EAW حالة الأساسي. بالإضافة إلى ذلك، أظهر تحليل الراحة الحرارية باستخدام قيم EAW الزجاج الثلاثي، و4.8٪ مقارنةً بنموذج

بين -0.68 و0.98، مما أبقى شاغلي المبنى ضمن نطاق PMV أن أفضل حالة حافظت باستمرار على Fanger PMV الراحة الحرارية المحايدة أو قريباً جداً منه على مدار العام. في الوقت نفسه، تذبذبت أنظمة الزجاج المزدوج والثلاثي التقليدية خارج هذا النطاق.

(بمسافة قضبان 0.05 متر مكعب/متر مكعب SA2) EAW في أفضل حالة لأنظمة (U) حُسبت قيمة معامل انتقال الحرارة لتكون 0.12 واط/م².كلفن، متفوقاً بشكل ملحوظ على قيم الزجاج التقليدي (التي تتراوح بين 2.2 و5.8 واط/م².كلفن). تُبرز هذه المحسنة هندسيًا في تقليل أحمال الطاقة مع تحسين الراحة الداخلية بشكل كبير. يُقدم التصميم EAW النتائج إمكانيات أنظمة المقترح حلاً عملياً وسليماً وقابلًا للتطوير لأغلفة المباني الموفرة للطاقة من الجيل التالي

CHAPTER 1

INTRODUCTION

1.1 Background

Maintaining thermal comfort presents a significant challenge in hot-humid climates. Traditional air conditioning systems, while effective, contribute to high energy consumption and greenhouse gas emissions, demanding alternative strategies [1]. As a critical component of building design, windows play a pivotal role in influencing indoor thermal conditions [2]. They serve as barriers to external environmental factors while enabling natural light and ventilation. However, conventional windows often fail to provide adequate thermal insulation, increasing energy demand for cooling in hot-humid climates [3].

Energy-active Windows (EAWs) emerges as a promising solution, dynamically controlling solar heat gain, thermal insulation, and ventilation. By integrating advanced technologies, these windows can regulate indoor environments more efficiently, reducing reliance on energy-intensive air conditioning systems. The dynamic properties of EAWs allow for the modulation of heat transfer and airflow, making them particularly suitable for maintaining thermal comfort in challenging climates.

This thesis addresses this research gap by investigating the integration of EAWs with airflow elements, capitalizing on their unique properties/profiles to enhance the occupant's comfort. These combined functionalities and the EAWs' dynamic control capabilities hold immense potential for optimizing thermal comfort in hot and humid regions.

While research on EAWs is ongoing, synergistic application in these specific climates necessitates further exploration. This thesis delves into this critical research gap, focusing on the meticulous selection and optimization of airflow elements for specific hot and humid conditions. Furthermore, it investigates the development of efficient and responsive control strategies for the integrated system and rigorously validates its performance through building simulations. Environmental considerations will also be meticulously evaluated to ensure that the proposed approach is effective and sustainable.

This study aims to significantly contribute to developing innovative building design solutions for achieving thermal comfort in hot and humid climates by addressing these critical research directions. This endeavor paves the way for a more sustainable and comfortable future, where buildings seamlessly integrate with their environment, fostering well-being for occupants while minimizing environmental impact.

1.2 Problem Statement

In hot climates, conventional window technologies often struggle to regulate indoor temperatures effectively and maintain thermal comfort, leading to increased energy consumption and discomfort for occupants. To address this challenge, this research focuses on integrating novel airflow configurations within energy-active window systems to

enhance thermal performance and indoor comfort. The primary objective is to assess the thermal performance of this innovative setup and its impact on indoor thermal comfort. Through a comprehensive investigation involving computational simulations, the study aims to evaluate the effectiveness of different airflow configurations in promoting convective heat transfer and reducing heat gain. The research further seeks to quantify the influence of these configurations on indoor temperature distribution and overall occupant comfort. Ultimately, this study aims to provide valuable insights for optimizing building designs in hot climates to achieve sustainable and comfortable indoor environments.

1.3 Objectives

This research aims to develop and optimize energy-active windows featuring advanced airflow elements to enhance thermal comfort in hot climate regions.

1. To review existing EAW and validate the selected CFD tool to ensure accurate and reliable study outcomes.
2. To evaluate the Thermal Performance of EAW by integrating Air Flow Elements with various geometric configurations.
3. To investigate the impact of various EAW alternatives on Thermal Comfort.

1.4 Scope & Limitations

1.4.1 Scope

The scope of this study encompasses the evaluation of novel airflow configurations integrated within an Energy-active window system for enhancing thermal performance and indoor comfort in hot climates. The research will involve the assessment of various airflow configurations, including circular, square, and triangular bars to optimize convective heat transfer and reduce heat gain. Computational simulations will be conducted to investigate the thermal performance of the proposed setup, including heat transfer rates, temperature distribution across window panes, and indoor comfort parameters. The research will contribute to advancing the understanding of innovative solutions for sustainable building designs in hot climates.

1.4.2 Limitations

Despite this study's comprehensive scope, several limitations should be acknowledged. Firstly, the research will focus specifically on evaluating the thermal performance and indoor comfort aspects of the proposed airflow configurations within EAW systems without considering other factors such as structural integrity, cost-effectiveness, and energy consumption. Furthermore, the effectiveness of the proposed configurations may vary depending on specific building designs, climatic conditions, and operational factors, which may limit the generalizability of the findings.

1.5 Rationale & Justification

1.5.1 Rationale

The growing demand for energy-efficient buildings has necessitated innovative solutions, particularly window systems, to improve building envelope thermal performance. Windows often represent significant weak points thermally, leading to increased heating and cooling loads and, thus, higher energy consumption. Conventional glazing systems (single, double, and triple glazing) have been widely investigated, but these remain limited in their ability to simultaneously optimize energy performance, thermal comfort, and indoor environmental quality. EAW systems present an advanced alternative, actively influencing thermal performance through controlled airflow, potentially enhancing indoor thermal comfort and reducing energy demand. Given the limited research exploring the integration of airflow elements (particularly geometric configurations such as square, circular, and triangular bars) within EAW systems, this study addresses the need for systematic investigation into their aerodynamic and thermal effects. The rationale is to thoroughly examine how different airflow elements influence heat transfer, airflow velocity, and thermal comfort within EAW systems, thus filling critical knowledge gaps in the current literature.

1.5.2 Justification

This study provides an essential contribution by systematically investigating the effectiveness of innovative geometric airflow elements within an Energy Active Window system. The validation of computational fluid dynamics (CFD) and energy simulations through well-established modeling tools (ANSYS Fluent and EnergyPlus/DesignBuilder) ensures robust, accurate, and reliable outcomes. Detailed analyses, such as grid independence tests, boundary condition sensitivity, and comprehensive monthly energy performance validation, underpin the scientific rigor of this research. Furthermore, comparing multiple geometric configurations (square, circular, and triangular bars) allows the identification of optimized airflow strategies that maximize heat transfer and thermal comfort while minimizing energy consumption. Consequently, the findings offer critical insights for architects, engineers, and policymakers seeking advanced techniques to achieve sustainable building designs and reduced operational costs, fully justifying the practical and academic significance of the research undertaken.

CHAPTER 2

LITERATURE REVIEW

2.1 Heat transfer mechanism in conventional window systems

Windows are glazed apertures with framing, shading, and one or more glazing (plastic or glass) in the building envelope [4]. Windows provide the least heat transfer resistance in a building envelope [5], [6]. In a typical house, windows account for roughly one-third of heat loss during the winter. Also, most of the air infiltration happens near the window's margins. Solar heat gain through the windows accounts for a significant portion of the cooling demand during the summer [7]. The overall influence of a window on a building's thermal balance is determined by the window's features and orientation, as well as solar and weather data.

A window is an integral feature of any building envelope [8] because it improves the building's appearance, lets light and solar heat in, and enables people to watch and observe outside their homes, even though they are so unwanted from an energy-saving standpoint [9]. Windows in low-rise structures can offer convenient escape routes in a fire or other emergency. Thermal comfort and energy efficiency are essential when choosing windows [10]. A window should effectively block heat transfer while allowing for sufficient light transmission. Making the most of natural daylight can help reduce a building's lighting needs [11].

By utilizing airtight double- or triple-pane windows with spectrally selective films or coatings and allowing in as much solar radiation as possible, heat loss through the windows during the winter can be reduced [12]. Effective internal or external window shading reduces heat gain and, thus, the cooling demand during the summer [13].

2.1.1 Heat transfer through double glazing window (DGW)

For the course of the study, this system serves as the reference system. It comprises a passive element and two 4 mm thick clear float glass panes. This system is a typical vacuum-insulated glazing unit (IGU) with an air gap that functions as an insulating layer in this instance based on a thickness of 12 mm. In addition to other sealing elements that preserve airtightness, spacers in the air space aid in maintaining the distance between the panes. The glazing would have a total thickness of 20 mm, as shown in Figure 1.

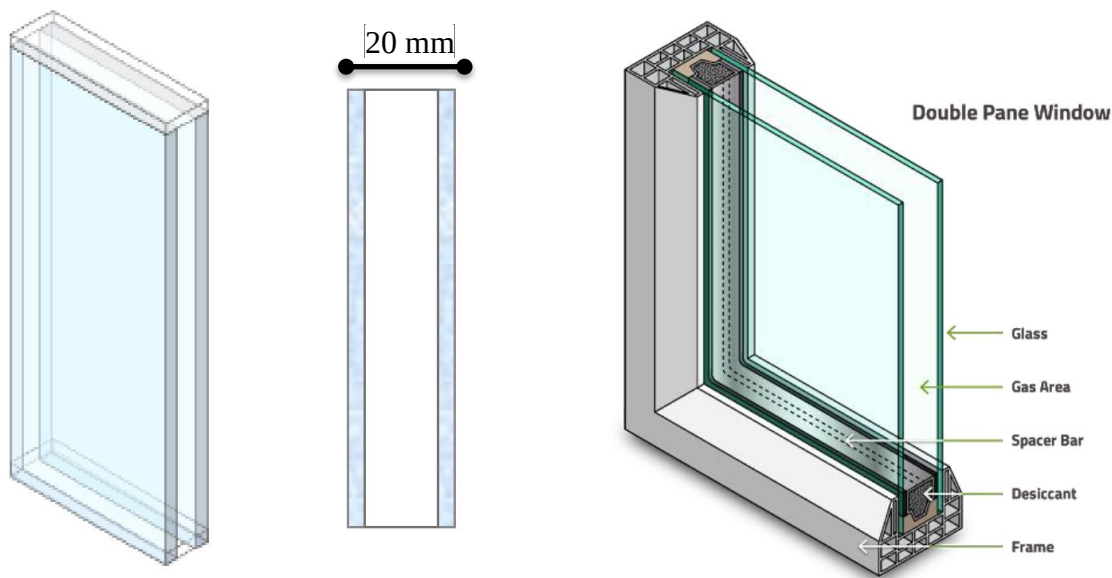


Figure 1. Schematic of double-glazing window

We'll consider heat transfer through conduction, convection, and radiation for a double-glazed window consisting of two glass panes separated by an air gap.

The equations ((1), ((2), (3), (4), and (5) for heat transfer through conduction, convection, and radiation can be written as follows:

Conduction through the glass panes

$$Q_{cond} = \frac{A \cdot (T_{\infty 1} - T_{\infty 2})}{2 \left(d_{glass} / k_{glass} \right) + \left(d_{air} / k_{air} \right)} \quad (1)$$

Convection on the inner glass surface

$$Q_{conv1} = h_{inner} \cdot A \cdot (T_{s1} - T_{\infty 1}) \quad (2)$$

Convection on the outer glass surface

$$Q_{conv2} = h_{outer} \cdot A \cdot (T_{s2} - T_{\infty 2}) \quad (3)$$

Radiation between the glass surfaces

$$Q_{rad} = \frac{\epsilon_{glass} \cdot A \cdot \sigma \cdot (T_{s1}^4 - T_{s2}^4)}{\left(1/d_{glass} + 1/d_{gap} + 1/d_{glass} \right)} \quad (4)$$

Total heat transfer

$$Q_{total} = Q_{cond} + Q_{conv1} + Q_{conv2} + Q_{rad} \quad (5)$$

To calculate the surface temperatures T_{s1} and T_{s2} , we must solve the above equations simultaneously. This can be done iteratively or using numerical methods such as finite element analysis (FEA) or computational fluid dynamics (CFD) simulations. These equations provide a comprehensive framework for analyzing heat transfer in double-glazed windows, as shown in Figure 2. They consider both the thermal properties of the materials involved and the convective and radiative heat exchange processes occurring at the glass surfaces.

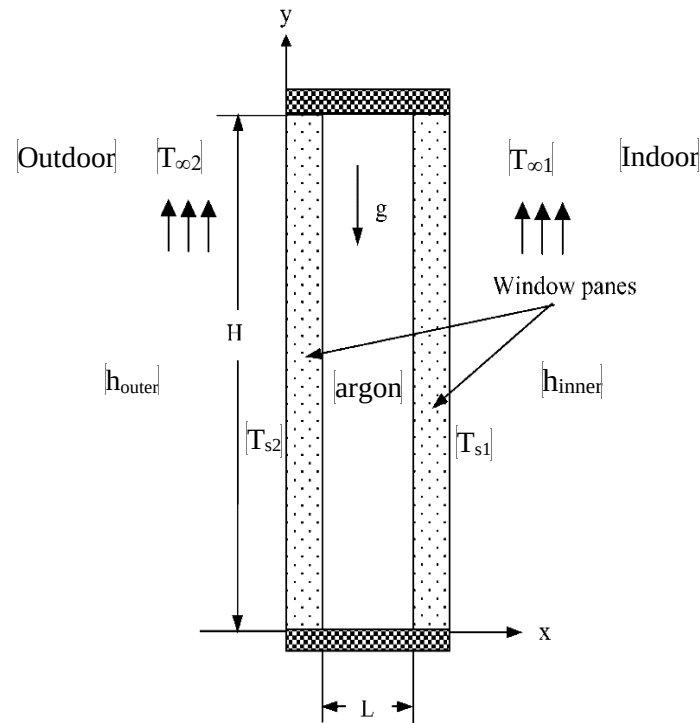


Figure 2. Heat transfer network of double-glazing window

2.1.2 Heat transfer through triple glazing window (TGW)

This window is thought to be competitive compared to EAW. It comprises two krypton-filled gaps in a passive super-insulated window. Windows of this kind are categorized as

low-E (low-emittance) products. It shall consist of three 4 mm glass panes with an inert gas, such as argon, between them. The overall thickness of this window assembly is 36 mm, with a gas area of 12 mm, respectively, as shown in Figure 3.

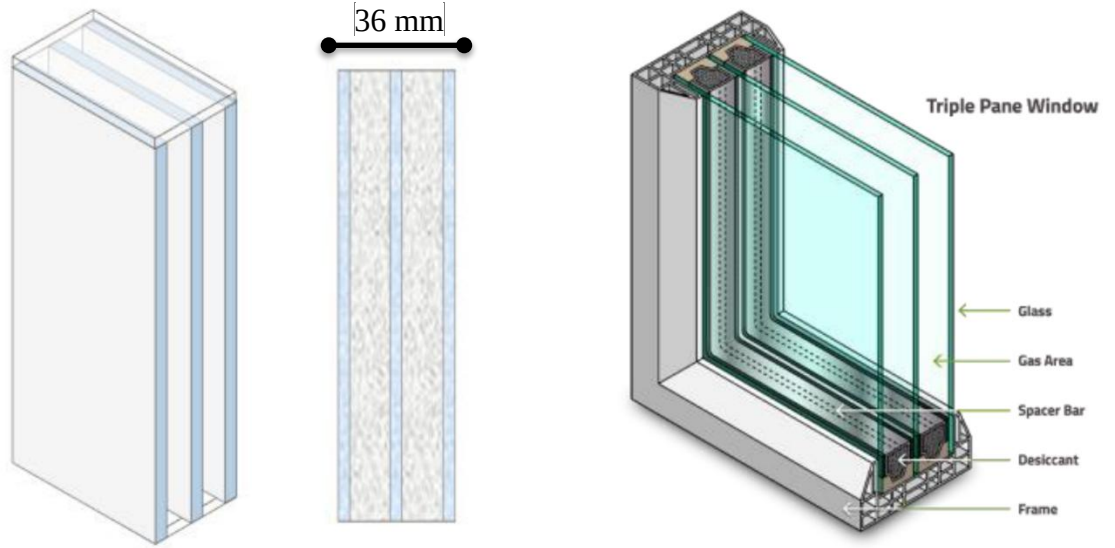


Figure 3. Schematic of triple-glazing window

The heat transfer equations for a triple-glazed window system should consider the middle glass pane. Every pane of glass contributes to the entire process of heat transfer, and the air spaces between them are essential for insulation. Consequently, each glass pane conduction, convection, and radiation, as well as the air gaps, should be taken into consideration in the proper formulation of equations (6), (7), (8), (9), and (10).

Conduction through the glass panes

$$Q_{cond} = \frac{A \cdot (T_{\infty 1} - T_{\infty 3})}{\left(d_{glass1} / k_{glass} + d_{gap1} / k_{gap} + d_{glass2} / k_{glass} + d_{gap2} / k_{gap2} + d_{glass3} / k_{glass} \right)} \quad (6)$$

Convection on the inner glass surface

$$Q_{conv1} = h_{inner} \cdot A \cdot (T_{s1} - T_{\infty1}) \quad (7)$$

Convection on the outer glass surface

$$Q_{conv2} = h_{outer} \cdot A \cdot (T_{s3} - T_{\infty3}) \quad (8)$$

Radiation between the glass surfaces

$$Q_{rad} = \frac{\epsilon_{glass} \cdot A \cdot \sigma \cdot [(T_{s1}^4 - T_{s2}^4) + (T_{s2}^4 - T_{s3}^4)]}{\left[\frac{1}{(d_{glass} + d_{gap1})} + \frac{1}{(d_{gap1} + d_{glass} + d_{gap2})} + \frac{1}{(d_{glass} + d_{gap2})} \right]} \quad (9)$$

Total heat transfer

$$Q_{total} = Q_{cond} + Q_{conv1} + Q_{conv2} + Q_{rad} \quad (10)$$

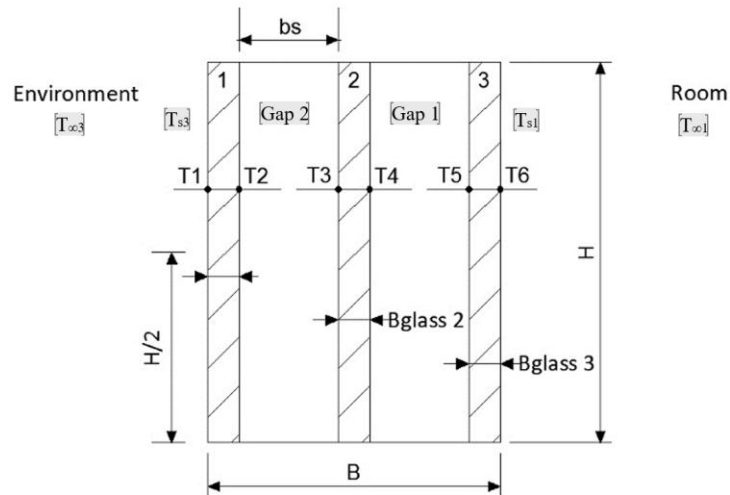


Figure 4. Heat transfer network of triple-glazing window

Figure 4 illustrates the thermal network of a triple-glazing window with glass thickness “b” and two gaps filled with inert gas. T_1 to T_6 are surface temperatures from outdoor to indoor environments.

A procedure for using consecutive approximations to solve the convective heat transfer problem through a double-glazed window was proposed [14]. This method effectively tackles any number of glasses in double-glazed windows. It comprehensively analyses how temperature differentials, gas layer thickness, and gas filler properties influence convective heat transfer resistance.

Another method [15] analyzed radiant-convective heat transfer in the central area of double-glazed windows, offering an analytical solution to the radiation heat transfer problem. Applicable to various double-glazed window types, it addresses specific low-emission coating configurations. The study explores reducing radiant heat losses by increasing glass count and incorporating low-emission coatings.

Heat transfer and fluid flow in double, triple, and quadruple-pane windows were examined numerically [16]. Different gap widths, external temperatures, and the inclusion and exclusion of radiative heat transfer are all considered while performing the computations. The findings indicate differences in the temperature profile and flow structure within the cavities of multiple-pane windows. Replacing a double-pane window with a triple-pane or quadruple-pane window will save approximately 50% or 67% of energy.

2.2 Previous studies relevant to EAW systems

Table 1 organizes papers by year, ID numbers, and research countries. The literature evaluation covers research from 12 countries: Sweden, China, France, South Africa, the UK, Denmark, Austria, Canada, Finland, Iran, the USA, and Hong Kong. Energy-active window technology functions differently in these countries due to varied climates. In Northern Europe, Sweden and Finland must reduce heat loss due to harsh winters.

The assessment emphasizes China, with its diverse climates. China's temperate north and tropical south are ideal for testing window technologies in fluctuating conditions. France and the UK exemplify these systems in moderate climates.

Due to subtropical and semi-arid climates, South Africa requires systems that handle extreme solar radiation and cooling. The US helps us understand these technologies in hot and cold temperatures. Hong Kong and Iran, known for their hot and humid climates, provide data on energy-active windows' efficiency where cooling and humidity control are crucial.

Table 1. Research studies/articles included in the review with their respective ID

Article IDs	Location	No. of Studies	Source	Reference	Year
Energy Active Windows					
{1}	Sweden	3	Scopus	B. Nourozi et. al. [17]	2020
{2}	Sweden		Scopus	B. Nourozi et. al. [18]	2020
{3}	Sweden		Web of Science	E. B. Villaplana [19]	2020

Article IDs	Location	No. of Studies	Source	Reference	Year	
Supply Air Windows						
{4}	France	16	Web of Science	F. Gloriant [20]	2015	
{5}	France		Scopus	F. Gloriant [21]	2021	
{6}	South-Africa		Scopus	M. Bhamjee et. al. [22]	2013	
{7}	France		Scopus	F. Gloriant et. al. [23]	2015	
{8}	France		Web of Science	Y. Huang et. al. [24]	2022	
{9}	UK		Web of Science	M. McEvoy et. al. [25]	2003	
{10}	UK		Scopus	M. McEvoy et. al. [26]	2004	
{11}	Denmark		Scopus	D. Bastien [27]	2019	
{12}	Austria		Scopus	S. N. Khosravi & A. Mahdavi [28]	2021	
{13}	France		Scopus	S. Zeiny et. al. [29]	2023	
{14}	France	5	Scopus	F. Gloriant et. al. [30]	2012	
{15}	Canada		Scopus	K. H. Haddad & A. H. Elmahdy [31]	2003	
{16}	France		Web of Science	F. Gloriant et. al. [32]	2013	
{17}	China		Scopus	J. Wang et. al. [33]	2017	
{18}	France		Web of Science	Y. Huang et. al. [34]	2023	
{19}	Finland		Scopus	Pertti Sarkomaa [35]	2003	
Exhaust Air Window						
{20}	Hongkong		5	Scopus	J. Guo & C. Zhang [36]	2022
{21}	China			Scopus	C. Zhang et. al. [37]	2019
{22}	Iran	Scopus		F. Khalvati & A. Omidvar [38]	2019	
{23}	China	Scopus		C. Zhang et. al. [39]	2016	

Article IDs	Location	No. of Studies	Source	Reference	Year
{24}	China		Scopus	C. Zhang et. al. [40]	2018
Dual Airflow Windows					
{25}	China		Scopus	C. Zhang et. al. [41]	2016
{26}	France		Scopus	G. Michaux et. al. [42]	2019
{27}	USA		Web of Science	J.R. Gosselin & Q. Chen [43]	2008
{28}	China	6	Web of Science	J. Wei et. al. [44]	2010
{29}	USA		Scopus	J. R. Gosselin & Q. Chen [45]	2008
{30}	China		Scopus	J. Wei et. al. [46]	2010

2.3 Energy active window systems: Research status

2.3.1 Energy active window (EAW) analysis

Several studies have assessed and improved the thermal performance of Energy-Active Windows (EAW) to reduce building energy use. Nourozi et al. [12] examined EAW thermal efficiency using two-dimensional finite differencing and critical parameter sensitivity analysis. At 20°C external temperature, EAWs reduced heating power demand by up to 2.2 W/m² floor area. The lower energy consumption of EAWs compared to triple-glazed windows emphasizes their thermal efficiency, especially in countries with high heating needs. Nourozi et al. [12] compared EAWs in cold-region, low-temperature heating systems to triple-glazed windows during the heating season. The study found that EAWs had much lower U-values (0.45 W/m²K) compared to TGWs (1.94 W/m²K), as EAWs'

superior insulating properties allow them to efficiently disperse buildings' peak heating demands, improving energy management during winter. The results show that EAWs can improve building energy efficiency, especially in cold climates, by reducing heating demand and improving thermal insulation. Another study [25] examined the environmental impacts and energy savings potential of EAW and compared this system with double-glazed units (DGU) and triple-glazed units (TGU).

2.3.2 Principles of energy-active window

A building has two types of environmental control systems: "passive" and "active" systems. These systems include the lighting, heating, and cooling systems.

Building envelopes that utilize natural resources like the sun, wind, and other elements to heat, cool, ventilate, and illuminate the built environment are called "passive" systems [47]. An "active system," on the other hand, generates or utilizes electricity on its own. It uses technology like heat recovery systems, solar panels, and renewable energy sources [48]. As anticipated, this technology aligns nicely with the goals that low-energy systems likewise want to achieve. It is implied that we are transforming low-temperature heating into high-quality energy when we use sustainable resources like earth heat, wind, sun, etc., to make electricity. The second law of thermodynamics states that the conversion efficiency is low.

The main function of the building envelope, which consists of the floors, walls, windows, doors, and roof, is to shield the occupants from the outside environment. Its functionality and design are key factors in controlling the indoor environment and establishing a

comfortable space. Good insulation is essential because it improves thermal comfort, even in large structures where internal gains may outweigh transmission losses [49].

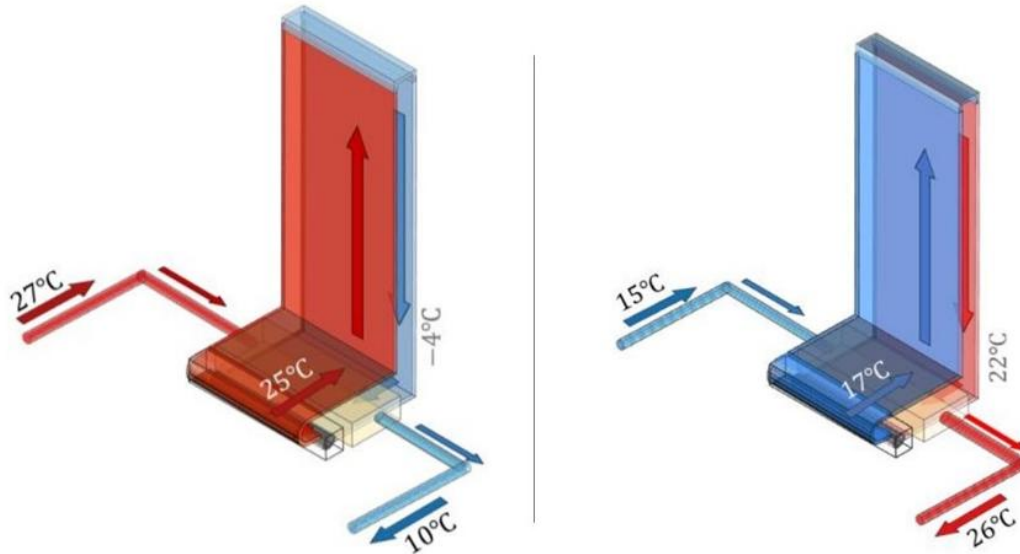


Figure 5. EAW during winter (left) and summer (right)

A building's parts' thermal transmittance is measured using various metrics. The one considered in this thesis is the $\text{W/m}^2\cdot\text{K}$ universal U-value, also known as the U-factor. Building components with good insulation have low thermal transmittance, while those with poor insulation have high thermal transmittance. Since walls, roofs, and floors have relatively efficient U-values of between 0.1 and 0.2 $\text{W/m}^2\text{K}$, windows, which can make up 10 to 25% of a building's exposed surface, are receiving increased attention [50].

Within a building envelope, windows serve as an interface for the transmission of light, the circulation of air, and the provision of an external view. The frame, sash, and insulated glazed unit (IGU) are the three primary parts of a window. However, they come in various sizes and designs [51].

An EAW uses cutting-edge methods to lessen and regulate the excessive heat inflow into buildings during summer, which lowers cooling requirements and improves indoor comfort. In winter, to minimize building heat loss, an EAW uses low-grade heat [6]. Figure 5 shows the visual representation of both these operations.

The main components of EAW include a double slot and insulation layer, an electric fan, a heat exchanger, air drivers, and wooden frames. Table 2 gives the two operations proposed by [47].

Table 2. Assumed nominal parameters by [52]

Winter Operation		Summer Operation	
T_{WI} of H_{ex} (T_{W in})	27°C	T_{WI} of H_{ex} (T_{W in})	15°C
T_{WI} of H_{ex} (T_{W out})	10°C	T_{WI} of H_{ex} (T_{W out})	26°C
T_{SA} to D_{slot} (T_{a out})	25°C	T_{SA} to D_{slot} (T_{a out})	17°C
T_{RA} from D_{slot} (T_{a in})	-4°C	T_{RA} from D_{slot} (T_{a in})	23°C
T_{ambient}	-20°C	T_{ambient}	25°C
T_{district heating}	50°C	T_{district heating}	10°C
T after U-floor heating	30°C	T after U-floor heating	13°C
Generic Parameters			
Mass flow air (m' a)	0.03 kg/sec		
Internal air speed (v_a)	0.24 m/sec		

2.3.3 Heat transfer mechanism in EAW

Radiation and convection are the two exterior and interior heat transfer mechanisms. Therefore, the research by [53] adopts the convective and radiative heat transfer

correlations for vertical plates. The proposed research will employ the above-mentioned study as a base case model and validation.

Since they are placed in series, the most significant thermal resistance determines the total thermal transmittance across the window. As a result, as this section shows, changes in the external heat transfer coefficient, which is greater than that of other window components, have no significant impact. This experiment uses a regularly known peak load calculation estimate for winters outside heat transfer coefficient, h_{out} .

Equation (11) Consider the empirical correlation of the average Nusselt number for natural convection over a vertical surface by [54]. This formula is true across the whole Rayleigh number range. The generic form of the equation approximates the convective heat transfer on the inner window surface. Lastly, the window's estimated U-value with energy balance is displayed in Equation (12).

$$Nu = [0.825 + \frac{0.387 Ra_L^{1/6}}{[1 + (\frac{0.492}{Pr_{in}})^{\frac{9}{16}}]^{\frac{8}{27}}}] \quad (11)$$

$$\frac{U_w}{h_{in}} = \frac{T_{in} - T_{surface,in}}{T_{in} - T_{out}} \quad (12)$$

In contrast to a traditional triple-glazed window, an integrated fan beneath the EAW controls the airflow between the panes in the slots, equivalent to the air mass flow rate. Both forced and natural convection transfer heat from the glass surface to the fan-driven airflow. The Richardson number $Ri = Gr/Re^2$ demonstrates each type's dominance. Figure 6 shows a thermal network across EAW.

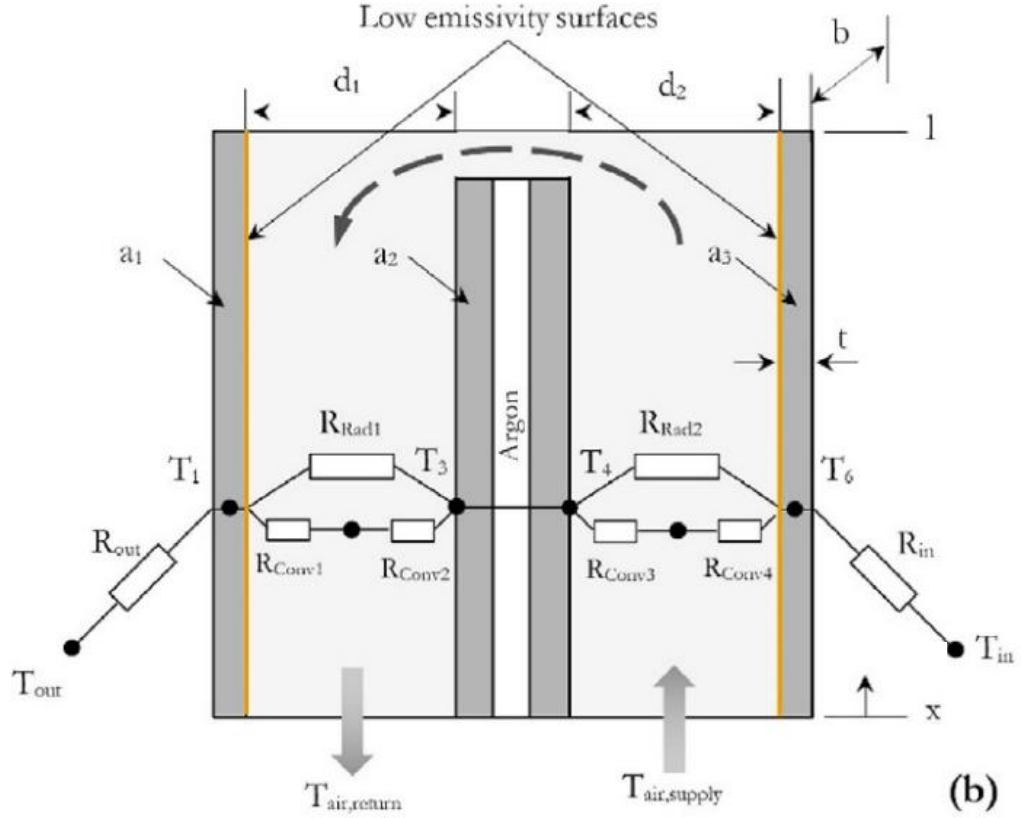


Figure 6. Thermal network in EAW

The predicted temperature at the various positions in the slot vertically and the window pane surface temperature is formulated in equations (13),(14),(15 presented in the base case model.

$$T_{air}^i = \frac{mc_{p,air}T_{air}^{i-1} + b\Delta x \sum_j (T_{surface}^{i,j} h_{convec}^{i,j})}{mc_{p,air} + b\Delta x \sum_j (h_{convec}^{i,j})} \quad (13)$$

$$T_{surface}^{i,j} = \frac{k \frac{bt}{\Delta x} (T_{surface}^{i-1,j} + T_{surface}^{i+1,j}) + b\Delta x (T_{surface}^{i,j} h_{rad}^{i,j} + T_{air}^{i,j} h_{convec}^{i,j} + T_{in/out} h_{in/out})}{2k \frac{bt}{\Delta x} + b\Delta x (h_{rad}^{i,j} + h_{convec}^{i,j} + h_{in/out})} \quad (14)$$

$$T_{surface}^{i,j} = \frac{k \frac{bt}{\Delta x} (T_{surface}^{i-1,j} + T_{surface}^{i+1,j}) + b\Delta x (T_{surface}^{i,j-1} h_{rad}^{i,j-1} + T_{air}^{i,j+1} h_{convec}^{i,j+1} + T_{argon} h_{argon})}{2k \frac{bt}{\Delta x} + b\Delta x (h_{rad}^{i,j-1} + h_{convec}^{i,j+1} + h_{argon})} \quad (15)$$

Where the air mass flow rate is m , T_{air}^{i-1} is the air temperature in the preceding control volume, and $h_{convec}^{i,j}$ is the heat transfer coefficient across the window panes. $T_{surface}^{i,j}$ is the temperature at window panes across the window cross-section, Δx is the grid size along the window height, and b is the window width.

2.3.4 Supply air window (SAW) analysis

The research on Supply Air Windows (SAW) examines energy performance, efficiency, and thermal behavior. A passive heat recovery system contributes to ventilation by enabling air renewal between the glazing before entering the building's interior. Experimental validations, CFD modeling, and field research show SAWs' potential and limitations. Wang et al. [38] use numerical simulations and full-scale experiments to prove the unsteady state zonal model of SAWs. They compare triple-glazed SAWs with built-in Venetian blinds to other windows in terms of energy use. Results show SAWs save 56.4% and 46.9% on cooling and heating energy compared to low-emissivity windows and windows with blinds, respectively.

Gloriant et al. [26] used simplified building modeling algorithms and CFD simulation to test the thermal performance of a triple-glazed SAW. The study revealed challenges in determining airflow and temperature distributions, especially at high airflow rates. Another survey by Gloriant et al. [27] used a full-scale experimental setup to examine the window

system's efficiency in reducing heating and cooling costs. Huang et al. [29] examine SAW dynamic U-values in ambient and window situations.

The study exhibits SAWs' adaptability by measuring window heat loss under different conditions. Bhamjee et al. [28] provide an empirically proven CFD model explaining SAWs. Despite discrepancies between experimental and CFD results, the study posits that SAWs can enhance thermal performance, necessitating updated turbulence models for free convective flows. D. Bastien [32] used LBNL WINDOW 7.6 to evaluate natural ventilation with a triple-glazed supply air window.

The results suggest effective U-values are lower, with a heat recovery efficiency of 38–58%. A study [34] characterized airflow and convective heat transfer in ventilated windows using a dual numerical and experimental approach. Sensitivity tests on turbulence models using K-e models demonstrated the transformation of a window into a heat exchanger.

2.3.5 Exhaust air window (E_xAW) analysis

Exhaust air windows (EAW) precool incoming air, reducing heating and cooling loads while boosting energy efficiency. Several studies investigated EAW thermal performance, energy savings, and applications. Guo and Zhang [41] studied the exhaust air glass unit (EAGU) and mechanical ventilation with heat recovery (MVHR) energy efficiency in Hong Kong in 2022. Using a zonal model for heat transport analysis and a numerical model for hourly loads, proven by experiments, EAGU outperformed MVHR systems in cooling but struggled in heating under different climates, saving 26.8% to 38.2%. EAGUs recover heat from exhaust air better in warm climates than cold ones.

Zhang et al. [42] tested a triple-glazed exhaust air window using low-grade exhaust air energy, employing a numerical model and experiments. Triple-glazed exhaust air windows reduced annual cooling and heating loads by 25.3% and 50.1%, respectively. Khalvati and Omidvar [43] investigated the thermal performance of exhaust airflow windows in Iranian structures cooled by evaporation, comparing window aspect ratio and air channel thickness to performance. Forced-ventilated windows had better convective heat transfer coefficients, cooling season exhaust, and external air curtain modes. EAWs saved 16.6% of energy over five months, reducing cooling capacity and improving occupant comfort. Zhang et al. [44] investigated heat movement through a switchable triple-glazing exhaust air window using a 2D zonal and numerical models. Adjustable exhaust air windows gain more heat than double- and triple-glazed windows. Exhaust airflow reduces window heat loss, enhancing thermal efficiency.

Zhang et al. [45] evaluated cooling-season triple-glazed exhaust air windows with Venetian blinds. "WINDOW" calculated U-values, and experimental tests validated the model. Airflow velocity and slat angles had lower U-values than traditional windows. The study recommended unsteady state zonal models for accuracy, reducing window heat gain by 42.3% in the cooling season.

2.3.6 Dual airflow window (DAW) analysis

Recently developed dual-airflow windows use incoming and outgoing air streams to increase energy efficiency and indoor air quality. Studies' analysis reveals their performance compared to conventional designs. Zhang et al. [22] used numerical calculations and experiments to examine the annual heat recovery of supply exhaust air

(SEA) windows. Results indicate SEA windows performed better at cooling, suggesting a preference in summer. However, they had lower heat recovery efficiency than standard total heat recovery ventilators (THRVs) during heating, highlighting the need to improve cold places.

Michaux et al. [46] compared triple-glazed airflow windows to double- and triple-glazed windows using numerical simulations and a nodal model. Results show energy needs dropped by 90% under daylight conditions, and the air supply heats up by 10-20 °C without sunlight. Airflow windows improve thermal performance and energy conservation, promising sustainable building materials. Gosselin and Chen [47] studied heat transfer and airflow in dual airflow windows. Their experiments showed that these windows can reduce the energy needed to heat incoming fresh air by 36% to 79%, depending on conditions. A study [49] investigated indoor air quality improvement and energy conservation through dual airflow window optimization.

The findings in Table 2 considered basic purpose, energy savings, thermal transmittance, tools, and standards used in each study, highlighting the need for further investigation in various climates. Figure 8 illustrates the energy-active window systems' design, functionality, and thermal dynamics. It emphasizes features of EAW's equipped with Venetian blinds for seasonal adjustments. Experimental configurations include full-scale and reduced-scale models illustrating boundary conditions for indoor and outdoor temperatures, airflow, and heat transfer mechanisms.

Cross-sectional thermal network diagrams demonstrate conduction, convection, radiation, and solar heat fluxes through window panes, highlighting their impact on thermal

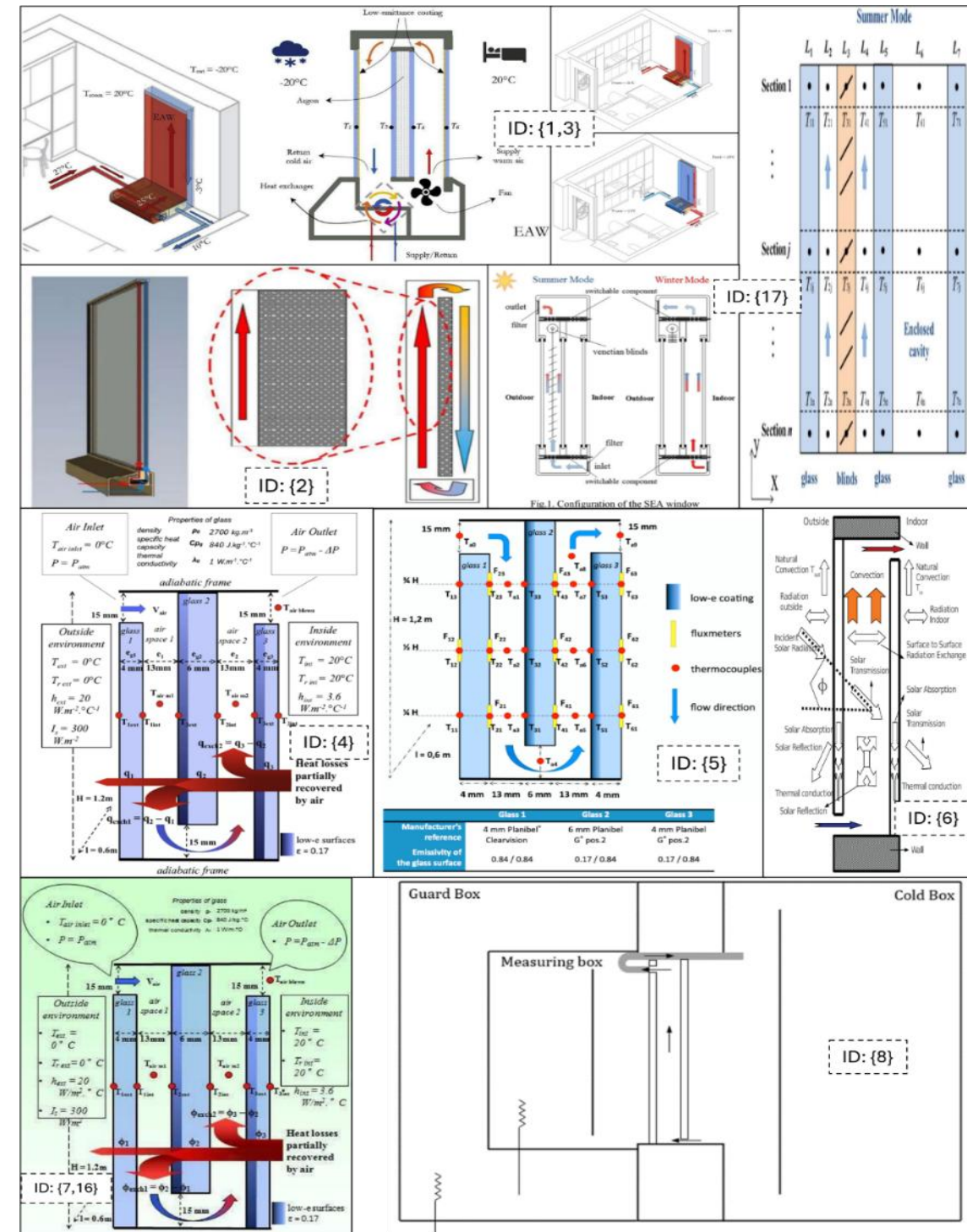


Figure 7. Cont.

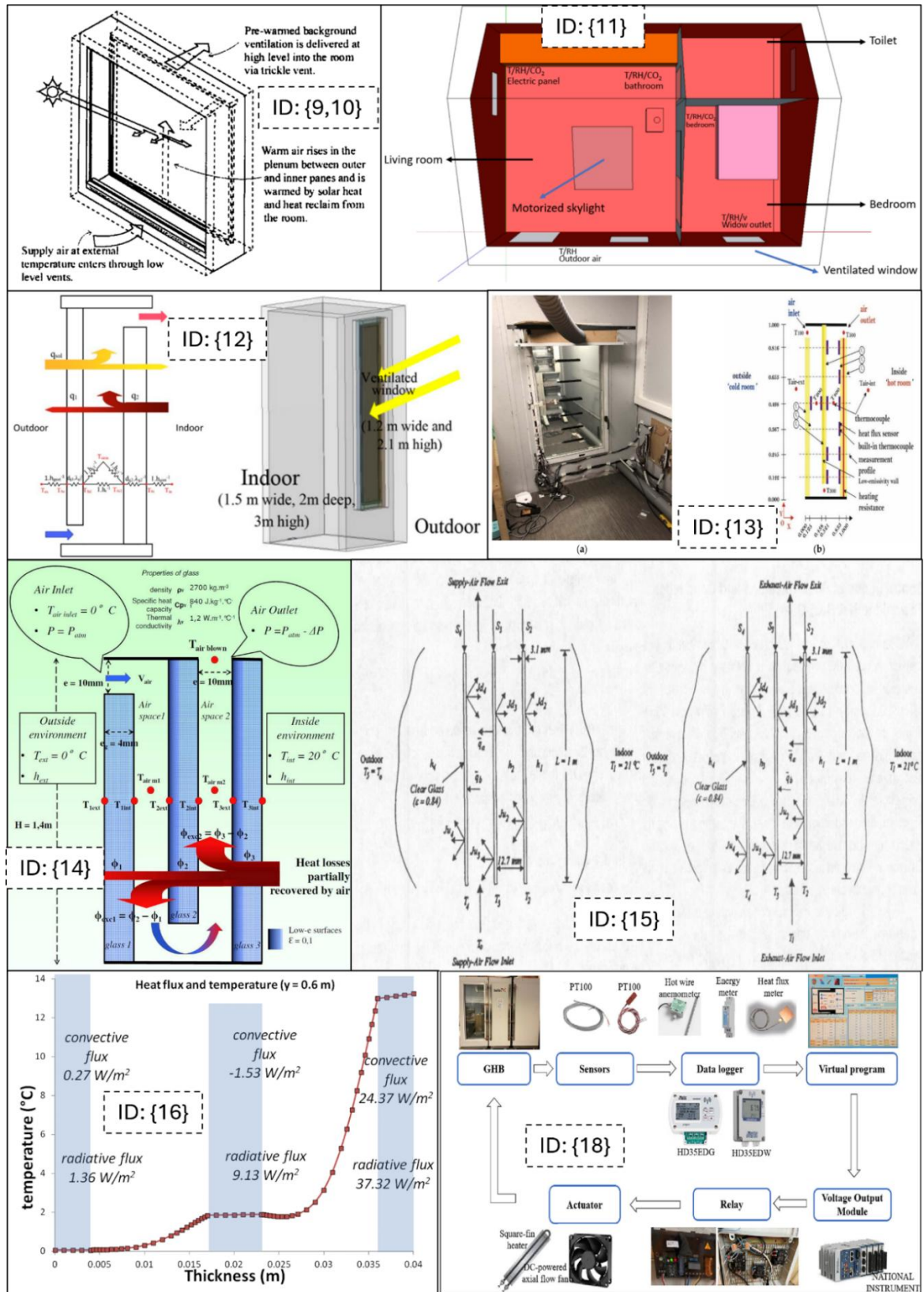


Figure 7. Cont.

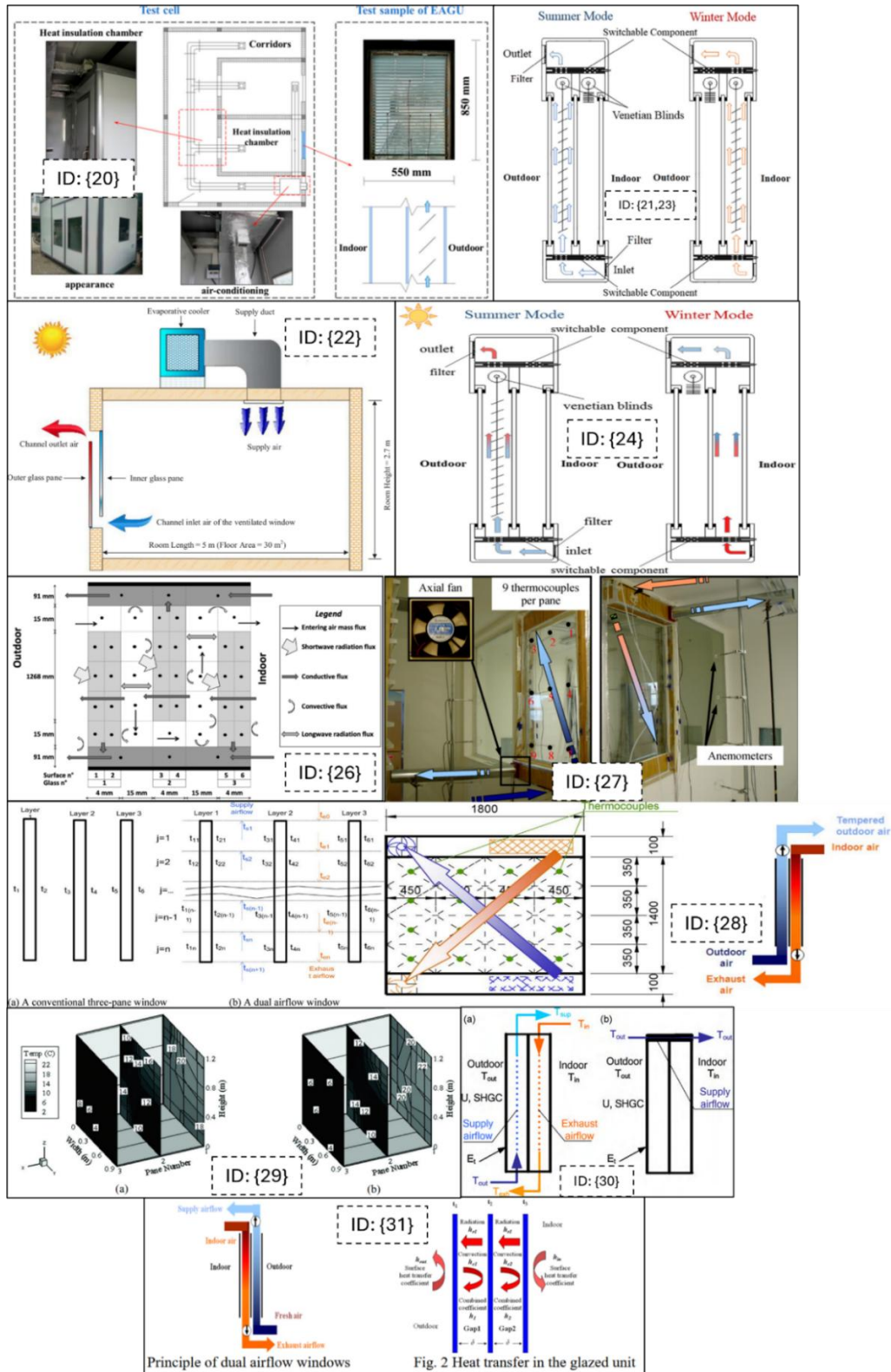


Figure 7. Graphic representation of the investigated “Energy-active window systems,” each referenced by article

Table 3. Summary of findings related to EAW systems between 2003 and 2023

No.	Title	Purpose/Focus	Method	Location	Results	Reference	Year
Energy Active Window							
1	Heat transfer model for energy-active windows (EAW): An evaluation of efficient reuse of waste heating in buildings. [17]	- The study evaluated EAW thermal performance, selected suitable Nusselt correlations, and assessed their relevance to the specific configuration. - Compared the thermal performance of the proposed window with a standard triple-glazed window.	- A two-dimensional finite differencing approach. - Conducted sensitivity analysis to assess the thermal performance of windows.	Sweden	The EAW reduced heating demand by 2.2 W/m² and 1.3 W/m² at outdoor temperatures of 20°C and 5°C, respectively, for a 10% window-to-floor area ratio.	B. Nourozi et. al.	2020
2	Integrated Energy Active Windows with Low-Temperature Heating Systems in Cold Climates. [18]	- Compared the thermal performance of energy-active windows (EAW) with conventional triple-glazed windows (TGW) during the heating season. - Evaluated the impact of lower U-values during peak winter hours on building heating loads.	Analytical heat transfer modeling using MATLAB.	Sweden	- EAWs achieved a lower U-value of 0.45 Wm-2K-1 compared to 1.94 Wm-2K-1 for TGWs. - Krypton gas in TGW slots reduced the U-value to 1.53 Wm-2K-1.	B. Nourozi et. al.	2020
3	LCC and LCA for Low-Temperature Heating Integrated with Energy Active Envelope Systems. [19]	- Evaluated EAW feasibility and cost-effectiveness over 20 years. - Assessed energy savings and environmental impacts before installation.	- Conducted LCIA using SimaPro and related models. - Quantified emissions and resources through LCI analysis.		- Minimal energy savings result in extended payback periods. - EAW complexity increases costs and emissions; slight energy improvements enhance environmental viability.	E. Villaplana	2020
Supply Air Windows							

No.	Title	Purpose/Focus	Method	Location	Results	Reference	Year
4	Modelling a triple-glazed supply-air window. [20]	- Evaluate the thermal performance of supply air windows using CFD simulations and develop simplified models. - Design and implement the Paziaud window in buildings, assessing global thermal performance indicators.	- Used CFD Fluent® software for window analysis. - Developed an Adapted to Building Simulation (ABS) model approach.	France	- The ABS1 model exhibits a decreasing exponential trend in air temperature. - The ABS2 model shows lower accuracy for airflow rates exceeding 15 m³.h⁻¹.	F. Gloriant et. al.	2015
5	Using heat flux sensors for a contribution to experimental analysis of heat transfers on a triple-glazed supply-air window. [21]	Assess smart windows' impact on energy performance, cost reduction, and occupant well-being.	- Experimental setup included thermocouples and heat fluxmeters. - Validated experimental data against numerical models using CFD Fluent.	France	- Fluxmeters improved heat transfer measurement accuracy near the window. - Experimental data validated using CFD Fluent.	F. Gloriant et. al.	2021
6	An experimentally validated mathematical and CFD model of a supply air window: Forced and natural flow. [22]	- Investigate experimental and computational methods for supply-air window analysis. - Validate CFD predictions with experimental temperature and velocity data.	CFD ANSYS Fluent 12.1 and Mathematical modeling for validation studies.	South-Africa	- Average error between CFD and experiment is 3.46K for temperature due to flow seeding and surface reflections. - CFD predictions qualitatively agree with the experiment but show a quantitative error.	M. Bhamjee et. al.	2013
7	Study of the Performances of a Supply-Air Window for Air Renewal Pre-Heating. [23]	- Investigate the performance of a supply-air window for air renewal. - Analyze factors influencing the thermal performance of the Paziaud® window.	- Numerical simulations using CFD and experimental work on a supply-air window. - Parametric studies to understand factors influencing the thermal performance of Paziaud® window.	France	- Higher air flow rate in the window leads to increased efficiency. - Low emissivity coatings on windows enhance performance.	F. Gloriant et. al.	2015

No.	Title	Purpose/Focus	Method	Location	Results	Reference	Year
8	Identification of dynamic U-values for supply-air double windows based on experiments. [24]	• Measure and propose dynamic U-values of supply-air windows based on ISO 15099, using varying environmental and window parameters. • Evaluate energy-saving potential and optimize supply-air window performance.	• Adapted guarded hot box experiments to measure U-values. • Applied regression analysis to correlate U-values with influential factors	France	• U-values depend on air flow rate and temperature difference. • Dynamic U-values can calculate window heat loss accurately. • The proposed T_{use}-value represents the heat recovery capability of supply-air windows.	Y. Huang et. al.	2022
9	Outdoor Measurements of the Influence of Aspect Ratio Performance on the Performance of Supply Air Windows. [25]	• Determine laminar flow feasibility in windows with different aspect ratios and compare heat loss across sizes. • Investigate U-value measurement challenges in window test cells.	• Whole test cell energy balance calculations. • Direct monitoring of U-values and detailed micro-measurements of temperature.	UK	• U_c-value dropped steeply during the day with no solar radiation. • Achieved very low U-values with statistical upper limits of 0.6 and 0.5 W/m²K. Aspect ratio is not a major factor in window energy performance.	M. McEvoy et. al.	2003
10	Description of a Program of Testing and Simulation to Establish the Determinants of the effective U-value of a ‘Supply Air’ Window. [26]	• Investigate factors influencing achievable U-values for 'supply air' windows. • Characterize their performance under various conditions and determine optimal insulation specifications.	• Lab test rig to investigate laminar or turbulent flows. • Mathcad Model simulations compared with experimental data to determine window performance. • Flovent package utilized for U-value analysis.	UK	• U-value reduction with decreasing temperature difference in experiments. • CFD analysis showed a U-value drop with changing ventilation rates.	M. McEvoy & R. Southall	2004
11	Natural ventilation with a supply air window and motorized skylight: A field study. [27]	• Evaluate the natural ventilation system with a triple-glazed supply air window under varying occupancies. • Assess heat recovery efficiency, IAQ, and flow	• LBNL WINDOW 7.6 is used for U-value calculations. • ISO 15099 was utilized for simulating a ventilated cavity.	Denmark	• Effective U-value 12-26% lower with heat recovery efficiency of 38-58%. • Dynamic airflow through ventilated windows influenced by local wind	Diane Bastien	2019

No.	Title	Purpose/Focus	Method	Location	Results	Reference	Year
		rates using the transient mass method.			conditions, with a flow rate between 27-42 m ³ /s.		
12	A CFD-Based Parametric Thermal Performance Analysis of Supply Air Ventilated Windows. [28]	- To Investigate the thermal performance of ventilated windows for preheating ventilation air. - To Analyze field characteristics and thermal behaviour of supply-type ventilated windows.	- ANSYS FLUENT 19.0 3D steady RANS CFD simulations for thermal behaviour of ventilated window cavities. - Applied measured data to evaluate the CFD model and examine heat gain.	Austria	- Taller cavities and smaller depths provide higher incoming air temperatures. - Windows with inner double-layered glazing show better thermal performance. - Ventilated windows can pre-heat incoming air for winter.	S. N. Khosravi & A. Mahdavi	2021
13	Analysis of the Thermo-Aeraulic Behavior of a Heated Supply Air Window in Forced Convection: Numerical and Experimental Approaches. [29]	- To characterize airflow and convective heat transfers in a ventilated window. - To highlight temperatures, velocities, and heat flux fields in the window.	- Dual numerical and experimental approach to characterize airflow. - Sensitivity tests on turbulence models using k-e models. - Conservation equations resolved using CFD Ansys-Fluent.	France	- Numerical modelling showed the window can be modelled as a heat exchanger. 'GEKO' model effectively reproduces flow in the window. • Air gap geometry impacts flow disturbances and heat exchanger uniformity.	S. Zeiny et. al.	2023
14	Supply air window PAZIAUD®: Comparison of two numerical models for integration in thermal building simulation. [30]	- To compare numerical models for SAW integration in building simulation. - To validate a simplified model for later use in numerical thermal code.	- Numerical model of hydrodynamics and heat transfer. - CFD Ansys-Fluent. - Full-Scale Experiment	France	This study has permitted defining performance factors for the supply air window and establishing its efficiency in the heat recovering of renewal pre-heating air.	F. Gloriant et. al.	2012

No.	Title	Purpose/Focus	Method	Location	Results	Reference	Year
15	Comparison of the Thermal Performance of an Exhaust-Air Window and a Supply Air Window. [31]	- To compare the thermal performance of supply-air and exhaust-air windows. - To assess energy efficiency and comfort levels of different window designs.	The VISION Program was used to Compare the thermal performance of supply-air and exhaust-air windows.	Canada	- Net heat gains of supply and exhaust-air windows are similar. - Exhaust-air windows outperform supply-air windows in terms of thermal comfort.	K. H. Haddad & A. H. Elmahdy	2003
16	Modeling Supply-Air Window in a Building Simulation Code. [32]	- Develop a model for SAWs in building simulations to analyze heat flux, air temperature, and pressure effects. - Improve air gap convective heat transfer coefficient calculations and resolve airflow window modeling constraints.	- CFD-Fluent is used for window modelling with a discrete ordinate radiation model for longwave radiation. - Analytical solution for air circulation between isothermal panes. - Implemented Modelica language with Buildings library.	France	- Discrepancies between model and CFD values highlight the need to improve convective heat transfer coefficients. - Proposed supply-air window model shows potential for building simulations. - Model applies to various supply-air window types.	F. Gloriant et. al.	2013
17	Energy Performance of Triple Glazed Window with Built-in Venetian Blinds by Utilizing Forced Ventilated Airflow. [33]	- Evaluate energy performance of triple-glazed SEA windows in different climates. - Validate unsteady state zonal model for SEA windows through experiments. - Compare SEA windows with low-e and blinds windows for energy efficiency.	- Numerical Simulations using the “VISION” computer program. - Full-Scale Experimentation (zonal model) - Agilent 34972A data logger for sensor signal recording.	China	- The proposed model accurately predicts SEA window thermal performance. - SEA windows reduce year-round energy consumption in cooling and heating seasons. - Annual energy consumption decreases by 56.4% compared to low-e windows and 46.9% compared to blinds windows.	J. Wang et. al.	2017

No.	Title	Purpose/Focus	Method	Location	Results	Reference	Year
18	Thermal performance characterization of supply-air double windows: A new guarded hot box protocol and numerical modulization. [34]	- To propose a new guarded hot box method for U-value testing. - Compare U-values of different window configurations for renovation potential.	- Proposed GHB methods for testing supply-air double windows, identifying U-values, and testing without mass transfer. - Built a 3D CFD model using ANSYS Fluent 19.0.	France	- U-values of supply-air double windows improved by 59.2%–80.8%. Low-E coating location and airflow rate impact U-values. - Deviations between window and center-of-glass U-values ranged 21.6%–45.5%. - Retrofitting reduces U-values by 59.2%–80.8%.	Y. Huang et. al.	2023
19	Energy saving through the use of a supply air window. [35]	Investigate energy savings and analyze heat transfer and recuperation ratio in the supply air window.	- Refrigerated chamber Simulation and modeling - Determination of recuperation ratio for supply air window.	Finland	- Overall heat transfer coefficients vary within specific values. - Supply air window reduces draft, energy consumption, and radiator size.	Pertti Sarkomaa et. al.	2003
Exhaust Air Window							
20	Utilization of Window System as Exhaust Air Heat Recovery Device and Its Energy Performance Evaluation: A Comparative Study [36]	To evaluate and compare the energy efficiency of the Exhaust Air Glass Unit (EAGU) and Mechanical Ventilation with Heat Recovery (MVHR) under various conditions.	- Zonal model for 2D heat transfer analysis of EAGU. - Numerical model to calculate hourly cooling and heating loads. - Validation with experimental measurements.	Hongkong	- EAGU saves 26.8% to 38.2% of energy in different climates. - EAGU outperforms MVHR in cooling but is inferior in heating. - EAGU is suitable for warm climates, not cold climates.	J. Guo & C. Zhang	2022
21	Numerical and experimental study on the thermal performance improvement of a triple-glazed window by utilizing low-grade exhaust air. [37]	- To investigate the thermal performance of triple-glazed exhaust air windows (TGEW). - To validate the numerical model and experimentally test the triple-glazed exhaust-air window.	- Two-dimensional numerical model - Experiment test to validate the numerical model	China	- TGEW reduces annual cooling and heating loads by 25.3% and 50.1%. - TGEW applies to buildings with fresh air supply systems.	C. Zhang et. al.	2019

No.	Title	Purpose/Focus	Method	Location	Results	Reference	Year
22	Summer study on the thermal performance of an exhausting airflow window in evaporatively-cooled buildings. [38]	- To investigate the impacts of window aspect ratio and air channel thickness. - To validate numerical approach with experimental data and propose geometric parameters for practical use in evaporatively-cooled buildings.	- Zonal model simulation validated with experimental data. - WINDOW software (Version 7.2) for acquiring radiative properties.	Iran	- Natural relief through the window can reduce cooling capacity and disturb occupants. - Forced ventilated window has a higher convective heat transfer coefficient. - Exhaust and outdoor air curtain modes are suitable for the cooling season. The average energy saving over five months is 16.6%.	F. Khalvati & A. Omidvar	2019
23	Modelling and thermal performance evaluation of a switchable triple-glazing exhaust air window. [39]	To evaluate the thermal performance of the switchable exhaust air insulation window and compare performance with conventional windows in heating and cooling seasons.	- Two-dimensional zonal model for thermal performance evaluation. - Numerical modeling with heat transfer processes. - WINDOW software for thermal performance analysis.	China	- Unsteady state zonal model accurately evaluates thermal performance - SEA windows outperform double and triple-glazing windows in heat transfer. - Exhaust air flow reduced heat loss and gain.	C. Zhang et. al.	2016
24	Experimental investigation and dynamic modelling of a triple-glazed exhaust air window with built-in Venetian blinds in the cooling season. [40]	- To investigate heat transfer and thermal performance of switchable exhaust air windows. - To utilize low-grade energy from exhaust air and achieve better thermal performance with larger airflow velocity and slat angle.	- Experimental tests for validation of the proposed model. - WINDOW software calculated U-values for conventional and SEA windows. - Use of fictitious cavity method for view factor calculation.	China	- Larger airflow velocity and slat angle in SEA window improves thermal performance and reduces U-value significantly compared to conventional windows. - The heat gain through the window can be reduced as high as 42.3% in the cooling season.	C. Zhang et. al.	2018

Dual Airflow Window

No.	Title	Purpose/Focus	Method	Location	Results	Reference	Year
25	Numerical evaluation of heat recovery performance of a switchable exhaust air window. [41]	Investigate the annual heat recovery performance of SEA windows in both seasons and analyze total heat recovery ventilators (THRVs)' performance.	- Numerical Simulations - Full-Scale Experimentation (zonal model)	China	SEA windows perform better in the cooling season but have limited heat recovery, which is inferior to traditional heat recovery ventilators in the heating season.	C. Zhang et. al.	2016
26	Modelling of an airflow window and numerical investigation of its thermal performances by comparison to conventional double and triple-glazed windows. [42]	- Investigate thermal performance of innovative triple-glazed airflow windows compared to conventional double- and triple-glazed windows. - Validate the numerical model with experimental results for dynamic and static conditions.	- Numerical simulations with a nodal model of the airflow window. - Mathematical formulation expressed through a differential equation.	France	Proposes a new computational method for airflow and heat transfer.	G. Michaux et. al.	2019
27	A computational method for calculating heat transfer and airflow through a dual-airflow window. [43]	- Develop a computational method to assess dual-airflow window energy performance. - Validate the method with full-scale experimental tests.	- CFD FLUENT with radiation model. - VISION program for coding radiation calculations. - Experimental validation tests (Full-Scale).	USA	- Airflow windows outperform double- and triple-glazed windows in thermal performance and energy efficiency. - Reduced energy from 5% at night to 90% during daylight. There is a significant reduction in energy needed to heat the fresh air entering the room, by 36% and 79%, respectively. - Air supply preheating ranges from 10–20 °C without solar radiation.	J.R. Gosselin & Q. Chen	2008

No.	Title	Purpose/Focus	Method	Location	Results	Reference	Year
28	Energy performance of a dual airflow window under different climates. [44]	Evaluate dual-airflow window energy performance across climates and compare it with conventional windows.	Energy Plus simulation for energy performance analysis in different climate zones.	China	- Dual airflow windows reduce heating energy, ideal for colder climates. - Cooling energy reduction is less significant than shading, but they improve indoor air quality, suitable for all climates.	J. Wei et. al.	2010
29	A Dual Airflow Window for Indoor Air Quality Improvement and Energy Conservation in Buildings. [45]	- To optimize dual airflow window design for energy conservation, IAQ and heat exchange efficiency. - Validate CFD simulations for window performance optimization.	The research method combined CFD Fluent for 3D simulation, heat conduction, and manual calculations for heat exchange optimization.	USA	- Dual airflow windows enhance IAQ and conserve energy, with 20%–56% heat recovery efficiency. - Risk of condensation in humid conditions but strong overall potential. - Cavity widths below 9 mm were excluded for airflow windows.	J. R. Gosselin & Q. Chen	2008
30	Optimal design for a dual-airflow window for different climate regions in China. [46]	- Evaluate dual-airflow window energy performance vs. conventional windows to identify optimal design parameters across climates. - Use the orthogonal method to analyze 13 design parameters for energy conservation.	- Orthogonal method to identify key design parameters; Taguchi and listing methods for optimal window design. - Energy balance equations to calculate dual-airflow window performance. - EnergyPlus software for performance simulations.	China	- Dual-airflow windows save 25–34% of energy across climates; key parameters include outdoor air supply rate and window height. - Lower SHGC increases ER, and high shading coefficients are recommended for optimal performance.	J. Wei et. al.	2010

No.	Title	Purpose/Focus	Method	Location	Results	Reference	Year
31	Heat transfer performance of glazed units in dual airflow windows. [55]	Develop a new method to study triple-glazed units' heat transfer performance and rules.	- Experimental tests used a hot-box platform and ISO/EN models for heat transfer analysis. - Developed new method of calculating dual airflow windows.	China	- Heat transfer shifts from conduction to convection at a 16mm gap. - Equivalent height is negligible in U-value calculations, with a minimum U-value at 16mm gap width.	Sun Bo et. al.	2013

2.4 Main categories and characteristics of EAW systems

The study categorized primary research groups into 'investigate,' 'contribute,' and 'compare,' analyzing each for characteristics and article IDs (Table 4). Some studies investigated thermal performance, U-values, heat recovery efficiency, and energy savings, while others contributed to research methods, developed experimental setups, and optimized EAW systems. Some studies compared these advanced window systems with conventional double and triple window systems for energy and thermal performance.

Table 4. Key categorization of the research articles under examination and their particular characteristics.

Studies Type	Examined Characteristics	Article IDs with Reference
Investigative	• Thermal performance • U-values • Airflow characteristics • Energy consumption • Numerical modeling • CFD simulations • Experimental validation • Heat transfer analysis • Preheating ventilation air • Heat recovery efficiency • Dynamic U-values • Impact of aspect ratios • Natural ventilation • Thermal behavior • Energy savings • Optimization of window performance • Impact of flow seeding • Turbulence models • Solar radiation effects	{1} (Nourozi et al., 2020) [17], {2} (Nourozi et. al., 2020) [18], {3} (E.B. Villaplana, 2020) [19], {4} (Gloriant et al., 2015) [20], {5} (Gloriant et al., 2021) [21], {6} (Bhamjee et al., 2013) [22], {7} (Gloriant et al., 2015) [23], {8} (Huang et al., 2022) [24], {9} (Evoy et al., 2003) [25], {10} (Evoy et al., 2004) [26], {11} (D. Bastien., 2019) [27], {12} (Najaf et al., 2021) [28], {13} (Zeiny et al., 2023) [29], {14} (Gloriant et al., 2012) [30], {15} (Haddad et al., 2003) [31], {16} (F. Gloriant et al., 2013) [32], {17} (J. Wang et al., 2017) [33], {18} (Y. Huang et al. 2021) [34], {19} (P. Sarkomaa et al., 2003) [35], {20} (J. Guo & C. Zhang, 2022) [36], {21} (C. Zhang et al., 2019) [37], {22} (F. Khalvati & A. Omidvar, 2019) [38], {23} (C. Zhang et al., 2016) [39], {24} (C. Zhang et al., 2018) [40], {25} (C. Zhang et al., 2016) [41], {26} (G. Michaux et al., 2019) [42], {27} (J. R. Gosselin & Q. Chen et al, 2008) [43], {28} (J. Wei et al., 2010) [44], {29} (J. R. Gosselin et al.,

Studies Type	Examined Characteristics	Article IDs with Reference
		2008) [45], {30} (J. Wei et al., 2010) [46], {31} (Sun Bo et al., 2010) [55]
Contributive	• Experimental analysis • U-values measurement • Energy efficiency evaluation • Energy performance • CFD model validation • Heat flux sensors for heat transfer analysis • New guarded hot box method • Zonal modeling • Supply air window performance • Natural ventilation effectiveness • Development of building simulation codes • Heat recovery performance • Thermal performance enhancement • Indoor air quality improvement • Energy conservation strategies	{1} (Nourozi et al., 2020) [17], {3} (E.B. Villaplana, 2017) [19], {4} (Gloriant et al., 2015) [20], {5} (Gloriant et al., 2021) [21], {6} (Bhamjee et al., 2013) [22], {8} (Huang et al., 2022) [24], {10} (Evoy et al., 2004) [26], {12} (Najaf et al., 2021) [28], {13} (Zeiny et al., 2023) [29], {14} (Gloriant et al., 2012) [30], {15} (Haddad et al., 2003) [31], {16} (F. Gloriant et al., 2013) [32], {17} (J. Wang et al., 2017) [33], {19} (P. Sarkomaa et al., 2003) [35], {20} (J. Guo & Chong Zhang, 2022) [36], {21} (C. Zhang et al., 2019) [37], {22} (F. Khalvati & A. Omidvar, 2019) [38], {23} (C. Zhang et al., 2016) [39], {24} (C. Zhang et al., 2018) [40], {25} (C. Zhang et al., 2016) [41], {26} (G. Michaux et al., 2019) [42], {27} (J. R. Gosselin & Q. Chen et al, 2008) [43], {28} (J. Wei et al., 2010) [44], {29} (J. R. Gosselin et al., 2008) [45], {30} (J. Wei et al., 2010) [46], {31} (Sun Bo et al., 2010) [55]
Comparative	• Comparison of EAW and TGW thermal performance • SEA window vs. low-e and blinds windows • Thermal performance of supply air windows vs. exhaust air windows • Dual-airflow window vs. conventional double and triple-glazed windows • Energy performance in different climates • Exhaust air glass unit vs. mechanical ventilation	{1} (Nourozi et al., 2020) [17], {2} (Nourozi et al., 2020) [18], {3} (E.B. Villaplana, 2020) [19], {4} (Gloriant et al., 2015) [20], {7} (Gloriant et al., 2015) [23], {9} (Evoy et al., 2003) [25], {11} (D. Bastien, 2019) [27], {15} (Haddad et al., 2003) [31], {17} (J. Wang et al., 2017) [33], {18} (Y. Huang et al. 2023) [34], {20} (J. Guo & C. Zhang, 2022) [36], {21} (C. Zhang et al., 2019) [37], {23} (C. Zhang et al., 2016) [39], {24} (C. Zhang et al., 2018) [40], {25} (C. Zhang et al., 2016) [41], {26} (G. Michaux et al., 2019) [42], {28} (J. Wei et al., 2010) [44], {29} (J. R. Gosselin et al., 2008) [45], {30} (J.

Studies Type	Examined Characteristics	Article IDs with Reference
	• Experimental data vs. numerical model • CFD model accuracy • Energy savings	Wei et al., 2010) [46], {31} (Sun Bo et al., 2010) [55]

2.5 Methods used for investigating EAW systems

Table 5 indicates that the thirty-one publications analyzed included research approaches such as simulations, mathematical modelling, laboratory experiments, and full-scale experiments. Twenty-four studies employed simulation technologies like CFD-ANSYS, Mathcad, MATLAB, EnergyPlus, SimaPro, and WINDOW. The studies' objectives and focus influence the diversification of simulation tools, as different programs have distinct strengths and drawbacks. Some tools excel at calculating energy consumption, while others are proficient in simulating heat transfer phenomena and thermal performance. Twenty-three studies utilized full-scale experimental methodologies, with several applying multiple approaches to ensure triangulation, verification, and validation. Utilizing various data gathering and analysis strategies is crucial to improving result reliability and accuracy. Nine investigations utilized mathematical modelling.

Table 5. Examined characteristics and main research methods adopted by reviewed research articles.

Methods Applied	Examined Characteristics	Reference {Article ID's}
Laboratory Tests/Full-scale	• Thermal & Energy Performance • Heat Transfer • U-values	Behrouz Nourozi et al., 2020 [17] {1}, Behrouz Nourozi et al., 2020 [18] {2}, F. Gloriant et al., 2021 [21] {5}, M. Bhamjee et al., 2013 [22] {6}, F. Gloriant et al., 2015 [23]

Methods Applied	Examined Characteristics	Reference {Article ID's}
experiments/Field experiments.	• Heat flux fields • Natural ventilation systems • Energy Savings • Mechanical Ventilation for heat recovery	{7}, Y. Huang et al., 2022 [24] {8}, M. McEvoy & R. Southall [25] {9}, M. McEvoy & R. Southall [26] {10}, Diane Bastien, 2019 [27] {11}, S. Zeiny et al., 2023 [29] {13}, F. Gloriant et al., 2012 [30] {14}, K.H. Haddad & A.H. Elmahdy, 2003 [31] {15}, J. Wang et al., 2017 [33] {17}, Y. Huang et al., 2023 [34] {18}, P. Sarkomaa et al., 2003 [35] {19}, J. Guo & C. Zhang, 2022 [36] {20}, C. Zhang et al., 2019 [37] {21}, F. Khalvati & A. Omidvar, 2019 [38] {22}, C. Zhang et al., 2016 [39] {23}, C. Zhang et al., 2018 [40] {24}, C. Zhang et al., 2016 [41] {25}, J.R. Gosselin & Q. Chen, 2008 [43] {27}, Sun Bo et al., 2013 [55] {31}
Simulation • ANSYS Fluent (CFD) • SimaPro • Mathcad • BEES • VISION • LBNL WINDOW • Flovent • EnergyPlus • MATLAB	• Thermal & Energy Performance • Heat Transfer • U-values • Energy Conservation & IAQ • Environmental Impact • Air channel thickness • Dynamic airflow • Convective heat transfer • Energy Efficiency	Behrouz Nourozi et al., 2020 [17] {1}, Behrouz Nourozi et al., 2020 [18] {2}, E.B. Villaplana, 2020 [19] {3}, F. Gloriant et al., 2015 [20] {4}, F. Gloriant et al., 2021 [21] {5}, M. Bhamjee et al., 2013 [22] {6}, M. McEvoy, R. Southall, 2004 [26] {10}, Diane Bastien, 2019 [27] {11}, S.N. Khosravi & A. Mahdavi, 2021 [28] {12}, S. Zeiny et al., 2023 [29] {13}, F. Gloriant et al., 2012 [30] {14}, F. Gloriant et al., 2013 [32] {16}, J. Wang et al., 2017 [33] {17}, Y. Huang et al., 2023 [34] {18}, C. Zhang et al., 2019 [37] {21}, F. Khalvati & A. Omidvar, 2019 [38] {22}, C. Zhang et al., 2016 [39] {23}, C. Zhang et al., 2018 [40] {24}, C. Zhang et al., 2016 [41] {25}, G. Michaux et al., 2019 [42] {26}, J.R. Gosselin & Q. Chen, 2008 [43] {27}, J. Wei et al., 2010 [44] {28}, J.R. Gosselin & Q. Chen, 2008 [45] {29}, J. Wei et al., 2010 [46] {30}, Sun Bo et al., 2013 [55] {31}
Mathematical Modeling	• Thermal Performance • Energy Performance • Heat transfer	Behrouz Nourozi et al., 2020 [17] {1}, Behrouz Nourozi et al., 2020 [18] {2}, M. Bhamjee et al., 2013 [22] {6}, S. Zeiny et al., 2023 [29] {13}, F. Gloriant et al., 2012 [30] {14}, J. Guo & C. Zhang, 2002 [36] {20}, C. Zhang et al., 2019 [37] {21}, C. Zhang et al.,

Methods Applied	Examined Characteristics	Reference {Article ID's}
		2016 [39] {23}, G. Michaux et al., 2019 [42] {26}

2.6 Terminologies used for EAW systems

Various researchers have used different terms to describe energy-active window systems (Table 6), including energy-active windows (EAW), supply air windows (SAW), exhaust air windows (EAW), and dual airflow windows. The energy-active window system utilizes low-grade heat to reduce the building's heating load in winter. This analysis recorded three significant terminologies employed by three studies, as outlined in Table 5. The supply air window (SAW) documented three distinct terminologies, whereas the exhaust air window (EAW) and the dual airflow window had five and one terminology, respectively. The characteristics and functioning of these window systems primarily determine these terms.

Table 6. Various terminologies are used in EAW systems.

Sr. No.	Categories	Number of Studies	Terminologies	Reference [Article IDs]
1	Energy-Active Window (EAW)	3	• Energy-Active Envelope (EAE) • Energy-Active Window (EAW)	Behrouz Nourozi et al., 2020 [17] {1}, Behrouz Nourozi et al., 2020 [18]{2}, E.B. Villaplana [19]{3}
2	Supply Air Window (SAW)	3	• Guarded Hot Box (GHB) • Supply air window model with heat recovery system (PAZIAUD)	Y. Huang et al., 2022 [24] {8}, Gloriant et al., 2012 [30] {14}, Gloriant et al., 2013 [32] {16}, Wang et al., 2017 [33] {17}

Sr. No.	Categories	Number of Studies	Terminologies	Reference [Article IDs]
3	Exhaust Air Window (E _x AW)	5	• Adapted to building simulation (ABS) • EAGU: Exhaust Air Glass Unit • MVHR: Mechanical Ventilation with Heat Recovery • THRV: Total Heat Recovery Ventilator • SHRV: Sensible Heat Recovery Ventilator • Switchable exhaust air window (SEA)	J. Guo & C. Zhang, 2022 [36] {20}, C. Zhang et al., 2016 [39] {23}
4	Dual Airflow Window (DAW)	1	• Energy Performance criterion for dual airflow windows (ER)	J. Wei et al., 2010 [46] {30}

2.7 Energy savings of various energy-active window systems

The energy efficiency of various energy-active window systems, as shown in several studies and Figure 8 and Table 7, significantly reduces cooling and heating loads, resulting in overall energy savings. Nourozi et al. [12] calculated a reduction in heating power demand by 2.2 W/m²K floor area and 1.3 W/m²K floor area at Tout of -20 °C and 5 °C, respectively. For supply air windows, J. Wang et al., 2017 [38] found substantial cooling and heating load reductions of 56.4 and 46.9 kW, respectively. J. Guo & C. Zhang [41] found that exhaust air windows showed 38.2% energy savings, while C. Zhang et al. [42] reported cooling and heating load reductions of 25.3 and 50.1 kW, respectively. F. Khalvati and A. Omidvar [43] discovered that exhaust air windows could achieve 16.6% energy

savings. J. Wei et al. [48] documented 34% energy savings for dual airflow windows. J.R. Gosselin and Q. Chen [47] conducted two studies, showing 79% energy savings in one and identifying seasonal variations in the other, with 20% savings in winter and 56% in summer [49]. These findings highlight the effectiveness of these advanced window technologies in enhancing building energy efficiency.

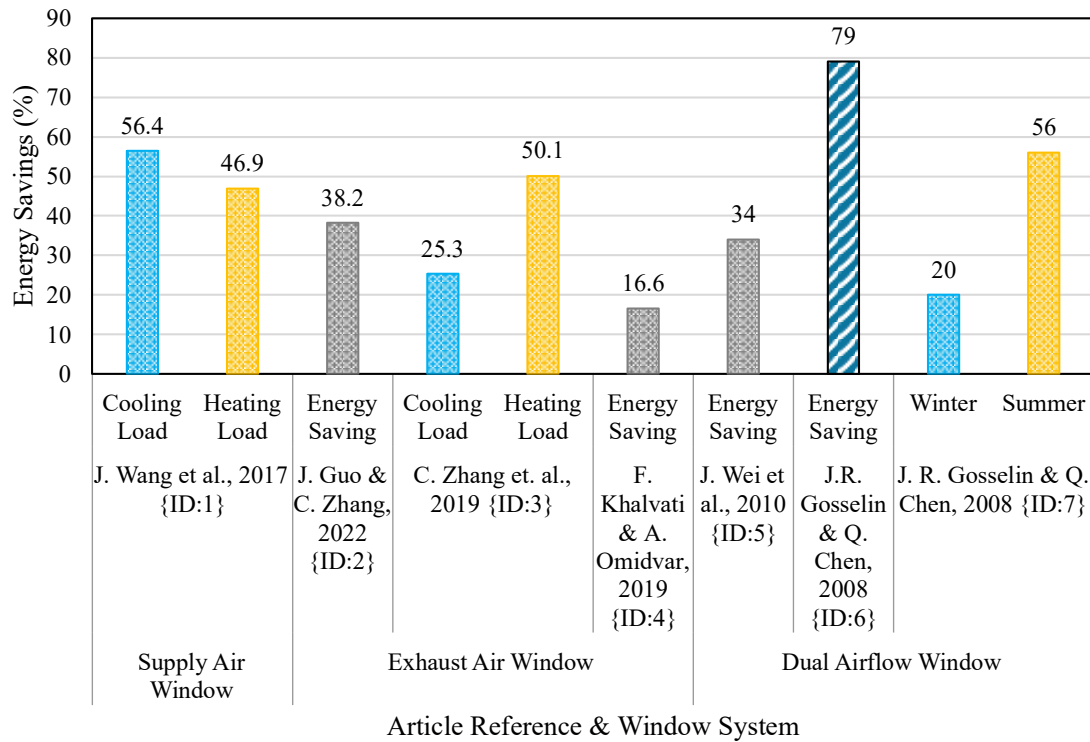


Figure 8. Energy saving potential as reported by some studies [33] [36], [37], [38], [43], [44], [45]

Table 7. Comparison of EAW systems by dimensions and energy-saving performance for cooling and heating applications.

Article's ID & Reference	Type of the Window	Size of the Window	Energy Saving (%)
--------------------------	--------------------	--------------------	-------------------

17 [33]	Triple-glazed window with Venetian blinds (SAW)	1.2 m x 2.0 m	Cooling: 56.4, Heating: 46.9
20 [36]	A test sample of EAGU (Exhaust Air Glass Unit) (E _x AW)	0.55 m x 0.88 m	38.2
21 [37]	Evaporative cooling ventilated window (E _x AW)	1.0 m x 2.0 m	16.6
22 [38]	Ventilated window with evaporative cooling (E _x AW)	1.0 m x 1.8 m	Cooling: 25.3, Heating: 50.1
27 [43]	Triple-glazed dual airflow window (DAW)	1.5 m x 3.0 m	79
28 [44]	Airflow window with dual functionality (DAW)	1.5 m x 1.5 m	34
29 [45]	Dual airflow window (DAW)	1.8 m x 1.2 m	Winter: 20, Summer: 56

2.8 U-values of various energy-active window systems

Figure 9 illustrates U-values for different window types from various studies. B. Nourozi et al. [12] reported U-values of 0.6 W/m². K and 0.45 W/m². K for energy-active windows. Studies by F. Gloriant et al. [20], M. McEvoy et al. [30], and M. McEvoy & R. Southall [31] found U-values of 0.3 W/m². K, 0.5 W/m². K, and 0.44 W/m². K for supply air windows. F. Gloriant et al. [20] found the best U-value of 0.3 W/m². K, indicating superior thermal performance. C. Zhang et al. [45] analyzed U-values for exhaust air windows under different conditions. In ventilated mode, with air velocities between 0.1 m/s and 0.5 m/s and a slat angle of 0°, the U-value was 0.94 W/m². K, while at a 90° slat angle, it decreased to 0.7 W/m². K. The non-ventilated mode recorded a U-value of 1.57 W/m². K has an air velocity of 0.5 m/s and a slat angle of 0°. This exhaust air window functions in both modes, making the ventilated mode more efficient. In this mode, exhaust air circulates between the

glass panes, improving thermal comfort and reducing cooling and heating demands. Increased airflow velocities, from 0.1 m/s to 0.5 m/s, lower the inner glass pane temperature and reduce heat gain. In non-ventilated mode, heat transmission occurs by conduction and radiation, reducing energy efficiency. The Venetian blind slat angle also affects performance. At 0° (blinds open), solar heat gain and glass temperature increase, while at 90° (blinds closed), solar radiation is blocked, reducing heat gain by up to 76.9%. Combining ventilated mode with a 90° slat angle maximizes thermal performance and energy efficiency. F. Gloriant et al. [20] demonstrated the best thermal performance with a supply air window U-value of 0.3 W/m². K.

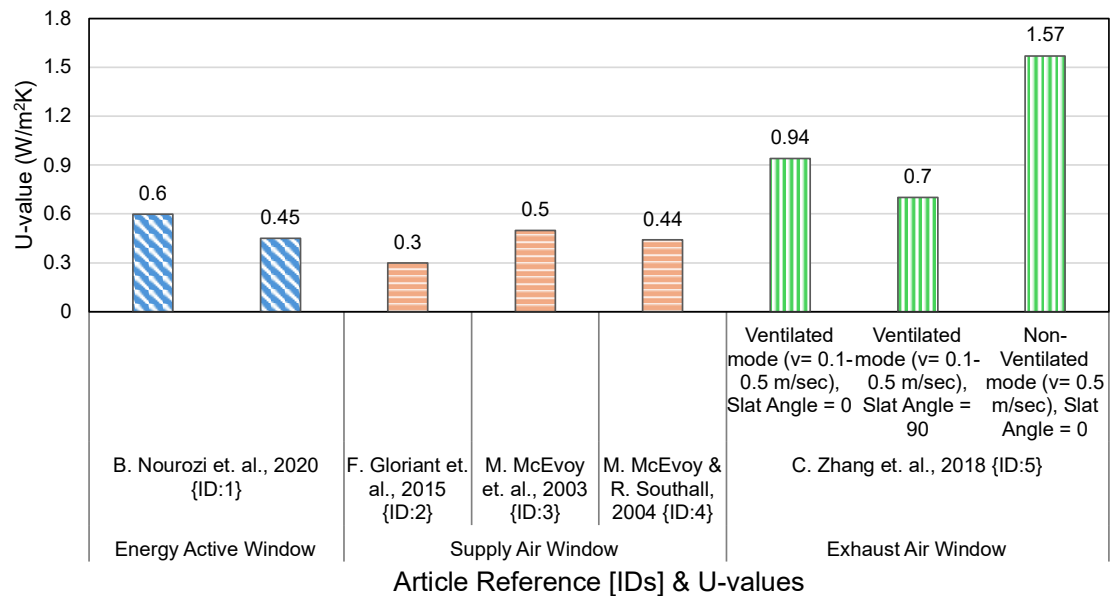


Figure 9. U-value of various EAW technologies reported by some studies [17], [23], [25], [26], [40]

2.9 Airflow elements with various configurations

The proposed research integrates airflow elements within energy-active window systems to enhance convective heat transfer and optimize thermal performance in hot climates. The primary air flow element comprises three shapes of bars strategically positioned within the window slots, as shown in Figure 10. These bars are designed to induce turbulence and disrupt airflow patterns passing through the window, thereby increasing the contact between the moving air and the panes.

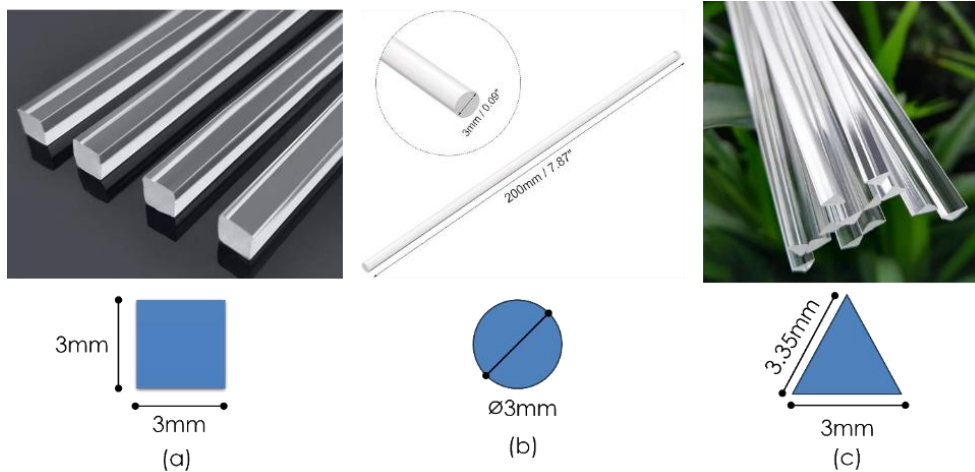


Figure 10. a) square bar, b) circular bar, c) triangular bar

This configuration facilitates efficient heat exchange, allowing the air to absorb heat from the window panes as it passes through, reducing heat ingress into the indoor environment. In the proposed EAW system, three distinct bar configurations square, circular, and triangular are integrated into the window air slots to enhance airflow dynamics and convective heat transfer [56]. These polycarbonate bars, positioned at 0.1 m c/c, ensure an unobstructed view while modifying the aerodynamic behavior within the window system.

Their primary function is to facilitate air mixing, reducing the residence time of air as it passes through the slots, which in turn enhances heat uptake from the window panes. Each shape introduces unique aerodynamic characteristics that influence the effectiveness of heat transfer. The square bars, with a cross-sectional area of 9 mm^2 , generate the highest turbulence due to their sharp edges, enhancing convective heat exchange. The circular bars, having a cross-sectional area of 7.07 mm^2 (calculated from a 3 mm diameter), exhibit a more streamlined flow with reduced drag, allowing moderate turbulence generation. Meanwhile, the triangular bars, with the smallest cross-sectional area of 4.5 mm^2 , balance aerodynamic efficiency and turbulence, encouraging vortex shedding that optimizes localized mixing and heat dissipation.

2.10 Thermal comfort in hot, humid climates

Thermal comfort in hot and humid climates revolves around creating indoor conditions where individuals feel thermally satisfied despite the challenging environmental conditions[57]. In such climates, high temperatures coupled with elevated humidity levels can make it difficult for individuals to dissipate heat from their bodies through perspiration, leading to discomfort and potential health risks [58].

Achieving thermal comfort involves maintaining suitable indoor temperatures, managing humidity levels, and ensuring adequate ventilation and air movement [59]. Strategies such as efficient building insulation, shading, proper ventilation systems, and the use of cooling technologies (like air conditioning or evaporative cooling) are employed to mitigate heat gain, manage humidity, and enhance airflow [60].

Additionally, designing buildings with materials and structures that resist heat transfer and absorb less heat from the environment contributes to enhancing thermal comfort in hot and humid climates [61]. Overall, it involves a combination of architectural design, technological interventions, and environmental controls aimed at providing occupants with a comfortable and conducive indoor environment despite the challenging external conditions[62].

2.11 Standards and guidelines related to thermal comfort

Several standards and guidelines address thermal comfort considerations in various settings worldwide. Some prominent ones include:

i. ASHRAE Standard 55

Developed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Standard 55 offers guidelines for thermal environmental conditions for human occupancy. It provides specific recommendations and criteria for indoor temperature, humidity, air speed, and radiant temperature aimed at ensuring occupant comfort [63]. This study aims to fulfil the thermal comfort criteria given by this standard.

ii. ISO 7730

The International Organization for Standardization (ISO) published this standard, which focuses on ergonomic principles related to thermal comfort. ISO 7730 guides environmental conditions, thermal comfort parameters, and methods for evaluating and designing indoor environments to achieve optimal thermal comfort [64].

iii. CIBSE Guide A

Produced by the Chartered Institution of Building Services Engineers (CIBSE), Guide A provides comprehensive guidance on environmental design and energy use in buildings. It includes sections on thermal comfort criteria, design strategies, and calculations to achieve comfortable indoor environments [65].

iv. ASHRAE Standard 62.1

Another ASHRAE standard, 62.1, addresses indoor air quality in buildings and includes considerations for thermal comfort. It provides guidelines for ventilation rates and is a necessary quality parameter to maintain a comfortable and healthy indoor environment [66][67][68].

v. EN 15251

This European standard outlines requirements for indoor environmental quality in buildings. It covers aspects of thermal comfort, among other factors, and provides guidance on design parameters and performance criteria for achieving comfortable indoor conditions [69].

These standards and guidelines offer valuable insights and recommendations for architects, engineers, building designers, and facility managers to create and maintain indoor environments that meet acceptable thermal comfort levels for occupants. They consider factors such as temperature, humidity, air velocity, and radiant heat to establish optimal conditions for human comfort and productivity in various building types and climates.

CHAPTER 3

METHODOLOGY

This chapter outlines the detailed procedures, tools, and techniques for conducting the research. The overarching objective is to provide a comprehensive and transparent account of the steps taken to gather, analyze, and interpret data, ensuring the rigor and reliability of the study. From the simulation setup to the validation process, each aspect is clarified to offer insight into the robustness and validity of the findings. This methodology seeks to resolve the convoluted interplay between EAW and airflow elements through a numerical simulation, ultimately contributing to a refined understanding of their impact on thermal comfort in challenging climatic conditions.

3.1 Research design

Figure 12 shows the gradual research methodology for this project, which ensured a logical flow from conceptual comprehension to model validation and performance analysis. Phase I, as mentioned in the previous chapter, involved a complete literature assessment of Energy Active Window (EAW) systems, their components, operations, and building envelope thermal behavior. In Phase II, a literature-based case study was used to define model parameters and airflow characteristics for the CFD and EnergyPlus models. CFD simulation involves geometry creation, meshing, and a grid independence test to verify numerical findings. After confirming the base case model, phase III evaluated circular,

square, and triangular bar designs for thermal and comfort performance under steady-state settings. Phase IV required analyzing results and post-processing decisions. In Phase V, conclusions and recommendations were made. In parallel, EnergyPlus simulations using DesignBuilder assessed the suggested model's annual performance under real climate circumstances, incorporating geometry, activities, lighting, openings, and HVAC systems. This holistic study design thoroughly evaluates the base case and enhanced EAW system under different alternatives.

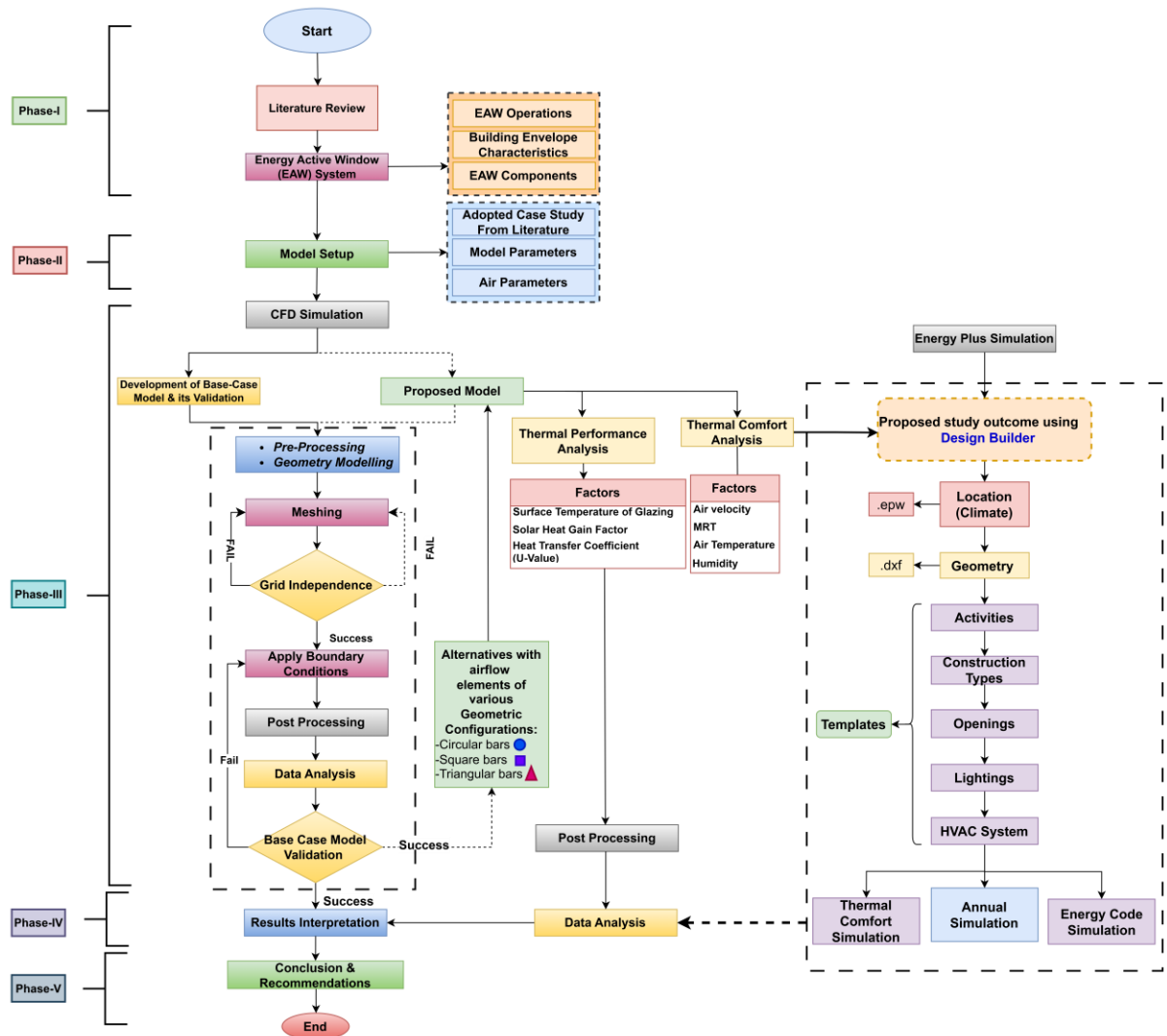


Figure 11. Research design methodology

3.2 Methods and materials

3.2.1 Research design and questions

The research design involved a systematic review following PRISMA guidelines for methodological rigour and transparency to address the research question: "What are the recent advancements in energy-active window technologies, and how do they contribute to energy efficiency, environmental quality, and sustainability in buildings?" This question explores innovations in energy-active window systems and addresses their impact on building energy performance and occupant well-being.

3.2.2 Literature search strategies

The initial stage involved identifying relevant records through a comprehensive search using Scopus and Web of Science databases. The search used keywords such as energy active windows, dual airflow windows, supply air windows, exhaust air windows, energy performance, and heat transfer. The analysis eliminated documents published before 2003 to focus on recent advancements. Researchers identified 75 articles and screened them at various levels.

3.2.3 Eligibility criteria

The study selection process followed PRISMA guidelines: identification, screening, eligibility, and inclusion. Initially, 75 records were identified, with 31 studies included for detailed analysis (Figure 11). Initial screening eliminated articles that did not address EAW

by reviewing abstracts and conclusions, leaving 55 articles. The second filtering removed papers that did not focus on heat transfer and energy conservation, resulting in 39 articles. The third step eliminated two papers due to non-English language or lack of full content access. The study evaluated 37 publications, analyzing their abstracts, introductions, methodology, and results to assess relevance. Evaluators excluded six articles for lacking a specific focus on EAW.

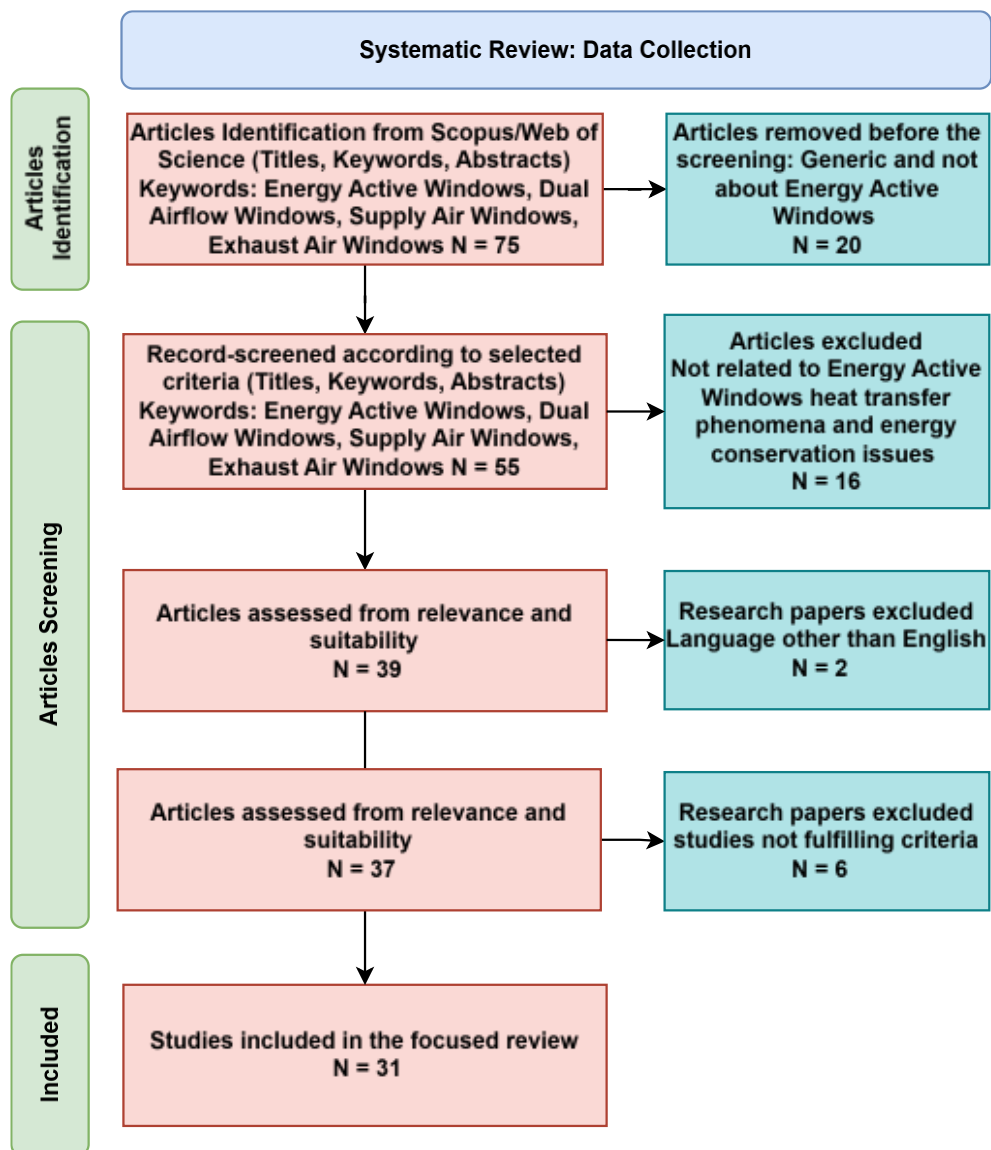


Figure 12. PRISMA flow diagram for systematic review data collection.

3.3 Simulation methodology

The present study uses CFD and EnergyPlus to simulate using a methodical approach. To precisely predict airflow and temperature distribution, the CFD program underwent validation using benchmark or experimental data. In parallel, the EnergyPlus tool validated the Mohammed Mohammed et al. [70] study and validated cooling loads (kWh) for several conventional glazing systems, proving its reliability. After validation, the CFD model was built to replicate double-glazed, triple-glazed, and a baseline Energy-Active Window (EAW) without airflow bars. Multiple EAW alternatives with integrated bar layouts were for airflow patterns and convective heat transfer. EnergyPlus simulations tested these alternatives' cooling energy performance in actual climates. This comprehensive approach compared thermal behavior and energy demand to find the best thermal performance configuration.

3.4 Validation of existing study by CFD simulations

The simulation methodology encompasses the procedures for conducting numerical simulations using ANSYS Fluent, validating an existing study by [53] and investigating the proposed case thereafter. This rigorous validation process ensures the accuracy and reliability of the selected CFD tool, establishing a solid foundation for subsequent analysis.

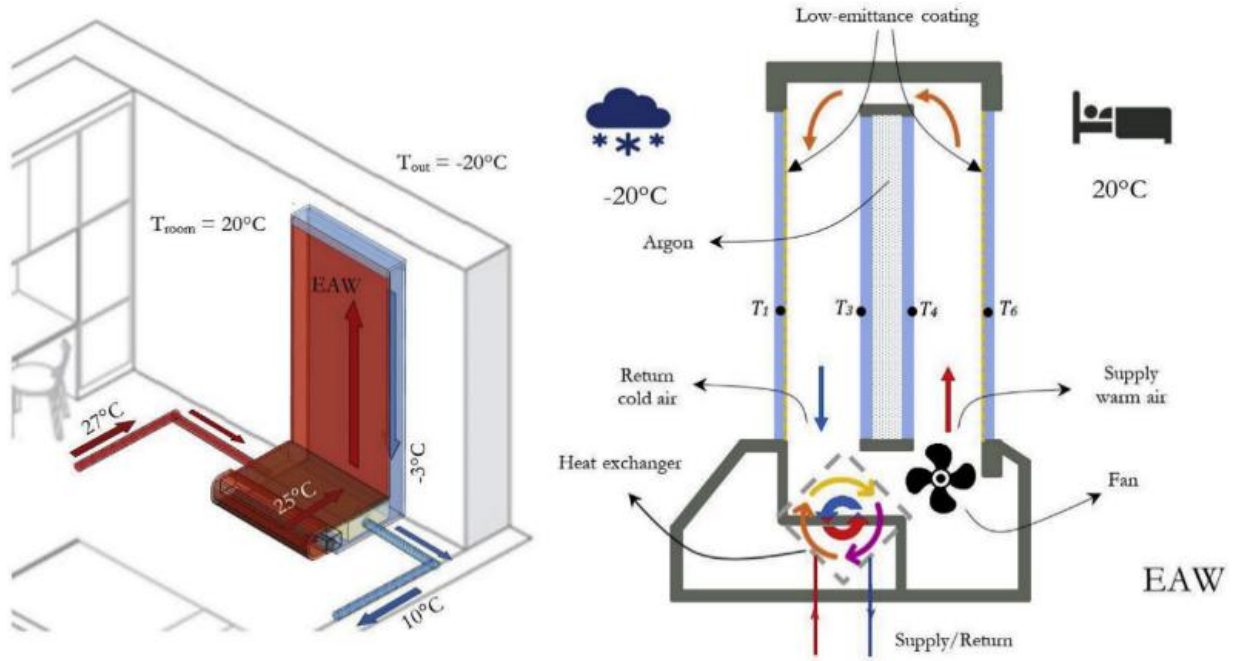


Figure 13. Illustration of EAW and heat source.

The parameters and boundary conditions in the existing study under validation are given below:

Table 8. Parameters & boundary conditions used in existing EAW study

Parameter	$L \times b \times t$	d_{slot}	U_{glass}	h_{out}	$\dot{m}_{\text{air}}$	T_{in}	T_{out}	ε
Unit	m^3	m	$\text{W.m}^{-2}.\text{K}^{-1}$	$\text{W.m}^{-2}.\text{K}^{-1}$	Kg/s	$^{\circ}\text{C}$	$^{\circ}\text{C}$	(-)
Value	$1 \times 1 \times 0.004$	0.01	5.75	34	0.003	20	-20	0.84 & (0.12)

To validate the previous study's findings, numerical simulations will be performed on the interconnectivity of CFD workflow elements, as shown in Figure 14. The simulations will replicate geometric parameters, boundary conditions, material properties, and solver settings as closely as possible.

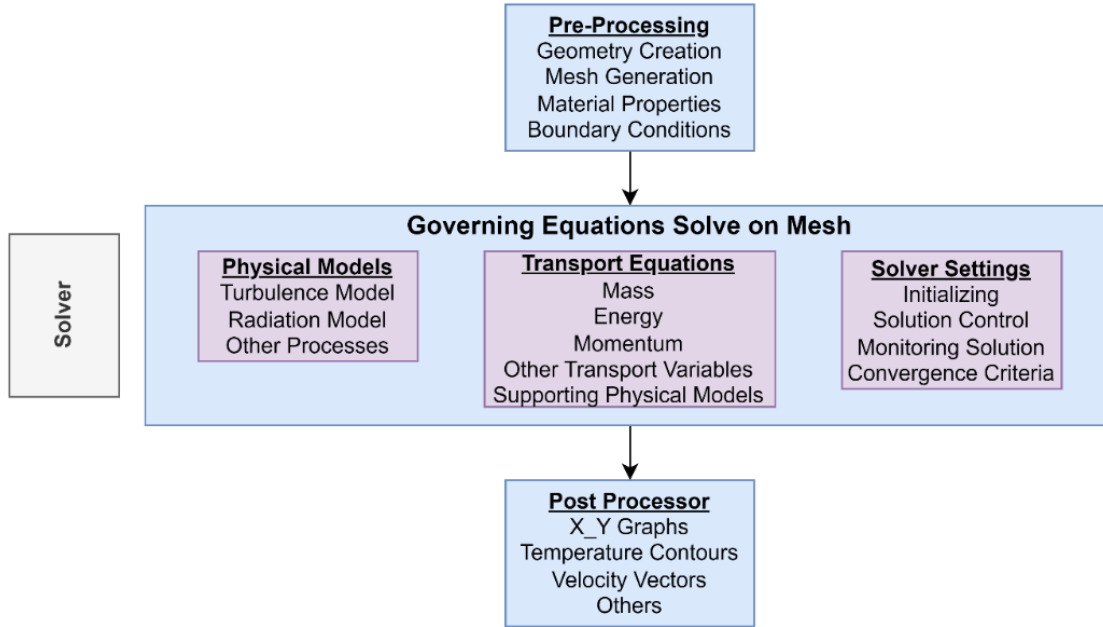


Figure 14. Interconnective functional elements of CFD.

As discussed earlier in the literature review, the existing study is based on the choice of best correlation of the Nusselt Number (Nu) corresponding to mixed convection within the slots of EAW. Moreover, the impact of the following parameters was taken into account in the existing study:

- i. EAW performance
- ii. Impact of temperature
- iii. Impact of slot size
- iv. Impact of airflow rate on EAW performance

As described in Table 2, geometric parameters can be visualized in Figure 2. The model represents the thermal/resistance network across EAW in transverse form. Also, the study calculated the change in temperature in the Y-direction along window slot d_s . Geometry

for the existing case study is developed in the design modeler, whereas meshing is done with physical preference as CFD and solver preference as Fluent, as shown in Figure 15. The element size is kept around 0.001 m, and the number of elements is 866445.

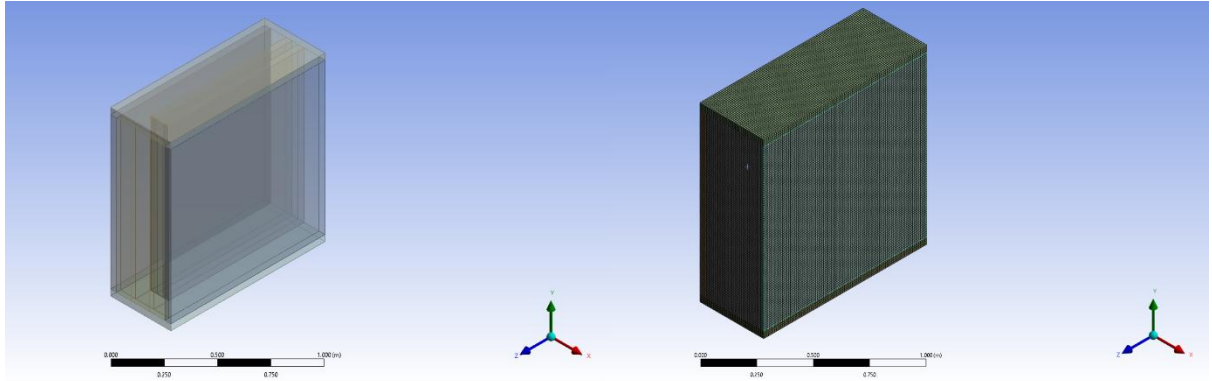


Figure 15. Geometry (on the left) and meshing (on the right) for the existing model validation

3.4.1 Validation of the present study through simulated outflow and inner glazing temperature for the EAW system

The validation of the present study for the simulated outflow temperature of the EAW system was conducted by comparison with results from two existing studies, as depicted in Figure 16 (a): the original research by Bergman [70] and a subsequent study by Nourozi et al. [17]. The comparison was carried out for airflow rates ranging from 4.5 L/s to 11 L/s, at a consistent inflow temperature of 23°C. The present study agrees excellently with Bergman's findings [70], showing a minimal deviation within $\pm 1\%$ across the entire airflow range.

The maximum deviation from Bergman's study occurs at the highest airflow rate of 11 L/s, presenting a minor error of approximately -0.8%, affirming the accuracy and reliability of

the numerical model utilized. In contrast, compared to Nourozi et al. [17], the present study systematically underpredicts the outflow temperature as airflow rate increases, with deviations starting at about 2% at 4.5 L/s and reaching as high as approximately -12% at 11 L/s. This divergence, particularly evident beyond 6 L/s, where errors exceed 7%, may indicate differences in computational assumptions, boundary conditions, turbulence modeling, or heat loss mechanisms, necessitating further examination into the influencing factors.

The present study's predictions for inner glazing temperature were validated by comparison with the findings from two reference studies, Bergman [70] and Nourozi et al. [17], as presented in Figure 16 (b). This validation spanned airflow rates between 4.5 L/s and 11 L/s. The present study maintains strong consistency across all airflow rates, closely aligning with reported results from both references.

Relative to Bergman's study [70], the predicted inner glazing temperatures exhibited deviations ranging from approximately -4.7% to -6.8%. Compared to Nourozi et al. [17], the deviations were notably smaller, consistently within -0.6% to -2.3%. The highest deviation of -2.3% from Nourozi et al. [17] was observed at the airflow rate of 11 L/s. These consistent and minor variations across increasing airflow rates underscore the capability of the employed numerical model in accurately capturing essential thermal behaviors, reinforcing its suitability for effectively predicting inner glazing temperatures under varied airflow conditions.

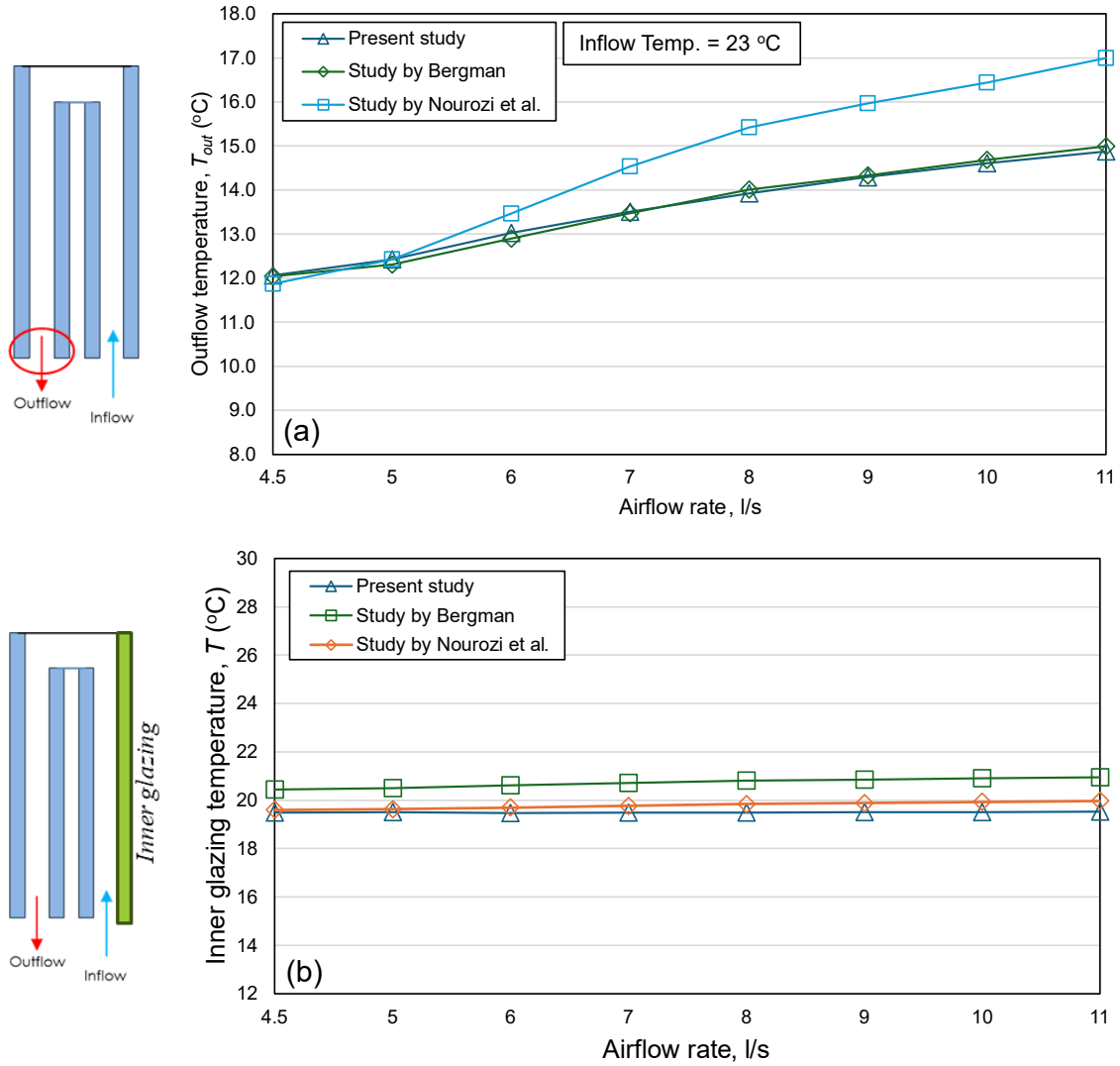


Figure 16. Validation of the present study through simulated a) Outflow temperature, b) Inner glazing temperature for EAW system

3.4.2 Validation of the present study for the triple-glazed window

The validation of the present study, as shown in Figure 17, temperature predictions for a triple-glazed window, was conducted by comparing the results with those obtained from [71] actual measurements and [17] study. The temperature difference values were analyzed to assess the accuracy of the present study.

For the outlet temperature, T_{out} , the present study shows complete agreement with both reference studies, with no difference observed. At T_1 , the temperature difference is noted to be 0.11°C compared to Larsson and 0.49°C compared to [17]. For T_2 , the deviation is slightly higher, with a difference of 0.56°C from Larsson's study and 0.54°C from [17].

The temperature at T_3 exhibits a difference of -0.90°C compared to [71] and 0.39°C compared to [17]. Similarly, at T_4 , the differences are -1.08°C and 0.56°C with [71] and [17], respectively. In the higher temperature range, at T_5 , the present study predicts a value of 1.36°C lower than [71] results, whereas the difference with [17] findings is -1.14°C . At T_6 , the deviations are smaller, with a difference of 0.15°C from the [71] study and -0.93°C from the [17] study.

For the inlet temperature, T_{in} , the present study matches both reference studies precisely, with no recorded difference. These results demonstrate that the present study's numerical approach closely aligns with experimental and computational data from previous studies, with temperature deviations remaining within a reasonable range across all measurement points. The observed differences highlight the precision of the model in predicting the thermal behavior of a triple-glazed window.

Comparing the Energy-Active Window (EAW) simulation model to experimental and numerical research confirmed it. Compared to Nourozi et al., Bergman et al., and Larsson, this study's outflow and inner glazing temperatures were consistent. Outflow temperature deviations rarely exceeded $\pm 4\%$, demonstrating a remarkable correlation with real-world data. The heat transfer across triple-glazed windows also correlated with Larsson's triple-glazed window research, confirming the model's thermal accuracy.

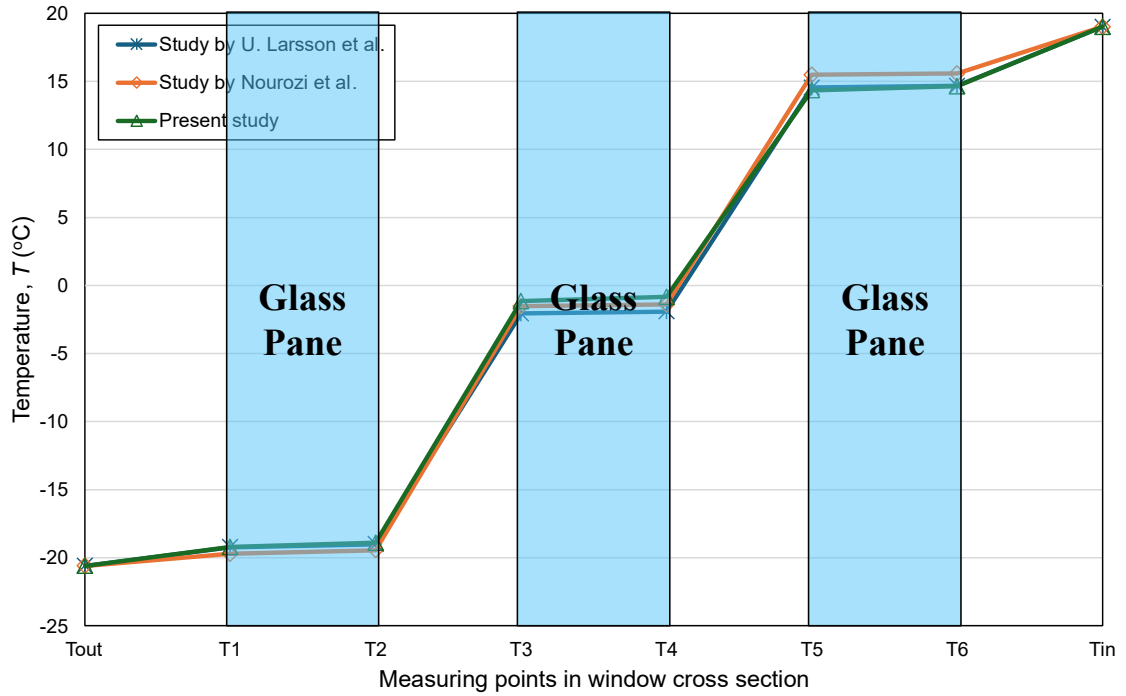


Figure 17. Validation of a triple-glazed window

3.5 Validation of the present study for energy consumption

calculation

3.5.1 Validation of the present study for single, double, and triple glazing

systems

The EnergyPlus (DesignBuilder) simulation model is validated by comparing monthly cooling electricity consumption results from the present study with previously published results for three different glazing configurations, as shown in Figure 19.

For the 3mm single clear glass, the monthly cooling energy consumption ranges between 1569.09 kWh to 5181.50 kWh in the literature, whereas the present study's results range from 1598.18 kWh to 5063.16 kWh. The percentage error varies between -4% to 4%, indicating good agreement. Most deviations are minimal, around $\pm 1\%$ to 2%, and larger deviations occur in the transitional months (February, May, October). This demonstrates that the single clear glass simulation is effectively validated.

In the 3mm double clear glass with a 6mm air gap case, the present study's cooling energy consumption (1667.34 kWh to 4609.63 kWh) closely matches the results of Mohammed et al. [70] (1664.24 kWh to 4781.98 kWh). The percentage error fluctuates between -4% to 4%, with the highest deviations observed in May (-4%) and August (4%). The overall error stays predominantly within $\pm 2\%$, reflecting high consistency and validating the double-glazed model effectively.

Finally, for the 3mm triple clear glass with a 6mm air gap, the cooling energy usage obtained from this study (1665.18 kWh to 4282.72 kWh) aligns closely with the literature (1679.25 kWh to 4503.14 kWh), with percentage errors mostly between $\pm 2\%$ to $\pm 5\%$. The maximum deviation (5%) occurs in August and October, possibly due to variations in climate data or modelling assumptions. However, these deviations are minimal and remain within an acceptable accuracy range, thus confirming the successful validation of the triple-glazed window.

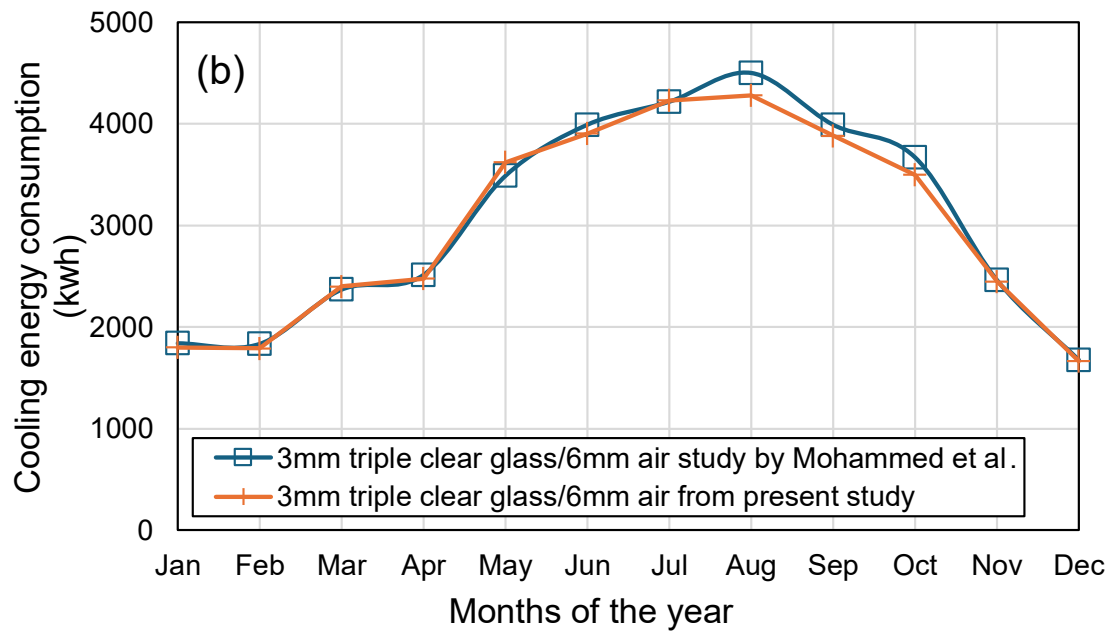
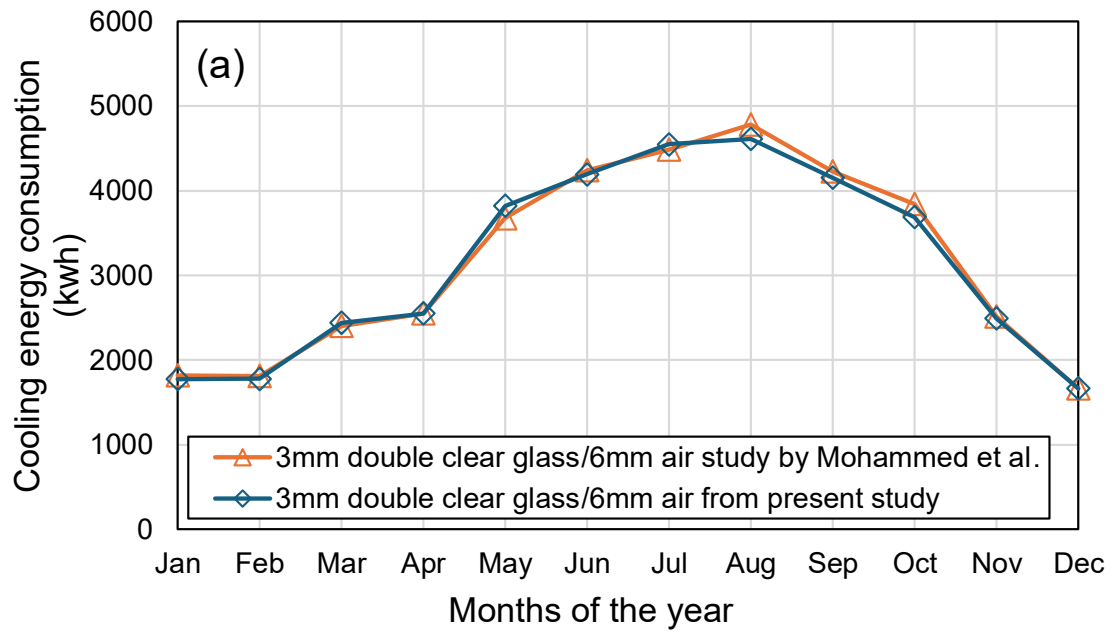


Figure 18. Validation of energy consumption (cooling energy, kWh) for: a) 3mm double clear glass/6mm air, b) 3mm triple clear glass/6mm air [70]

3.6 Proposed study

Subsequently, simulations will investigate the proposed case of enhancing thermal regulation and comfort in energy-active window systems by integrating airflow elements. The simulation setup for this proposed case will involve defining specific design parameters, configurations, and objectives tailored to the research objectives. By combining simulation methodology and validation procedures, this study ensures a comprehensive and systematic approach to evaluating and improving energy-active window systems in hot climates. The relationship between CFD and the heat transfer mechanism is shown in Figure 19.

Integrating airflow elements within energy-active window systems enhances convective heat transfer mechanisms, particularly during periods of intense solar radiation. In this process, indoor return air is utilized, where the fan, an integral component of the energy-active window system, plays a central role. The fan facilitates indoor air circulation, drawing it towards the window slot (internal flow) where the airflow elements are integrated. This induced airflow generates turbulence, effectively directing the air toward the window pane surface (combined). As a result, convective heat transfer rates between the air and the window surface are amplified, enabling efficient heat uptake and dissipation.

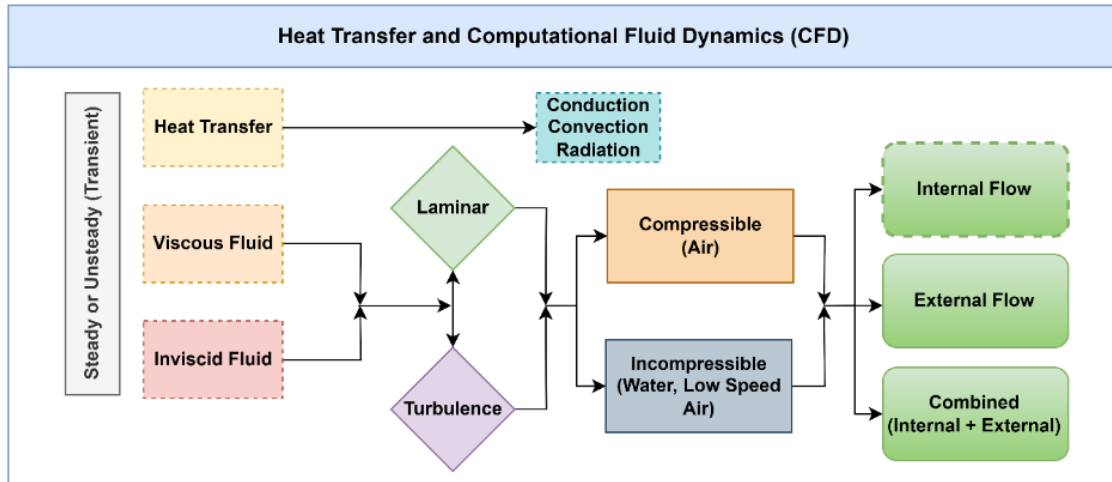


Figure 19. Heat transfer and CFD representation

Consequently, during peak solar exposure, the integrated airflow elements effectively mitigate heat transfer through the window, improving thermal regulation and enhancing occupant comfort. Through this mechanism, energy-active window systems optimize convective heat transfer, with the fan acting as a crucial component in facilitating air circulation and improving heat exchange efficiency. The proposed system is thus to be compared with the conventional double and triple glazing system (the profile of both these systems is discussed in the literature earlier). The simplified formulation of these systems under consideration is shown in Figure 20.

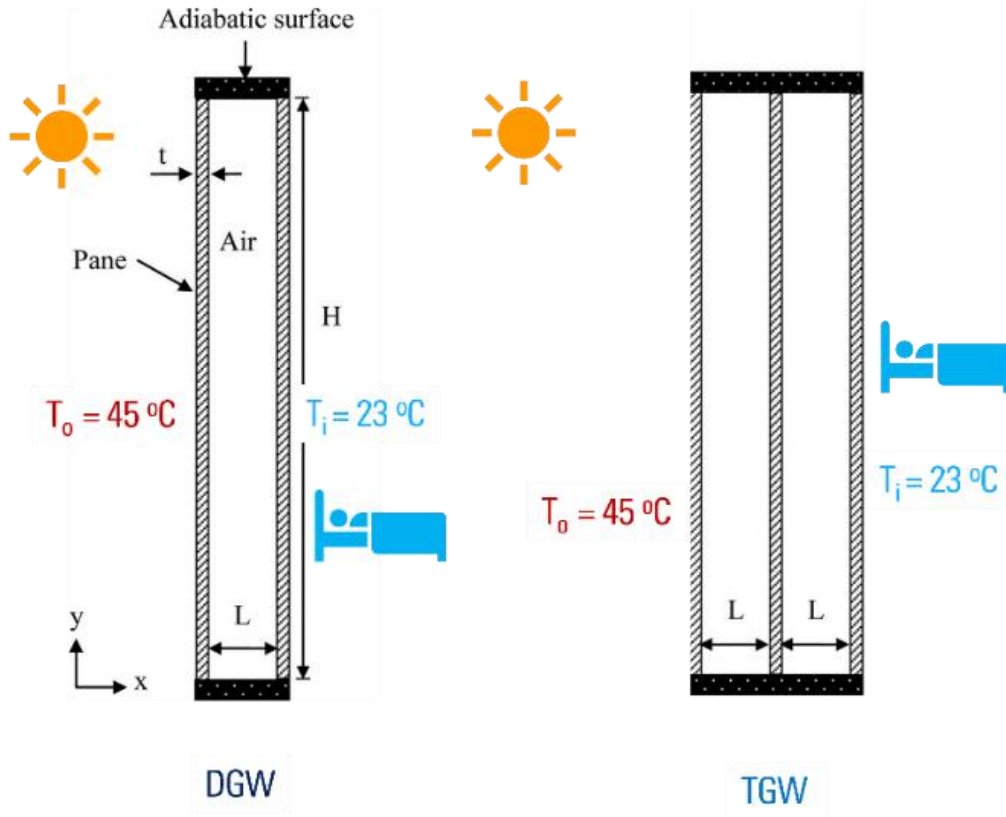


Figure 20. Schematic of DGW and TGW configurations

3.7 Geometry creation for CFD simulations

This section presents a detailed overview of the geometry creation process for the numerical simulations performed in this study. Initially, a base case geometry representing the Energy Active Window (EAW) system without airflow elements was developed to serve as a reference model. Following this, additional geometries incorporating airflow-enhancing elements—square, circular, and triangular bars with various spacing configurations—were created. All these alternative geometries were systematically prepared to reflect realistic conditions, ensuring consistency in dimensions and boundary specifications. Each geometric configuration was clearly defined, providing the basis for a

comparative analysis of airflow dynamics and thermal performance within the EAW system.

3.8 Base case geometry of EAW

The proposed base case of the EAW system, as shown in Figure 21, is designed to enhance thermal performance by integrating argon gas-filled cavities between four glass panes. The system optimizes heat transfer control through strategic thermal layering and specific boundary conditions, making it suitable for energy-efficient applications. Temperature measurement points T_1 through T_6 within the window system are strategically positioned to assess distinct thermal characteristics. Specifically, points taken at T_1 , T_3 , T_4 , and T_6 are located directly within the glass panes, whereas points T_2 and T_5 correspond to the airflow slots— T_2 represents the outflow air slot and T_5 the inflow air slot. These measurements (T_1 to T_6) are recorded across five distinct locations (P_1 to P_5) along the height of the window, starting from a height of 0.05 m at the lower portion (P_1) and extending upward to 0.85 m at the upper portion (P_5). Point T_1 and the adjacent T_2 capture heat transfer at the outer glazing surface and its associated outflow slot. The centrally located points on the surface of T_3 and T_4 evaluate heat retention efficiency within the argon-filled glazing region. Finally, points taken on T_5 and T_6 , positioned near the indoor-facing inflow slot and glazing, reflect the system's capability to reduce heat loss and maintain indoor thermal comfort. This vertical arrangement of points enables a comprehensive analysis of temperature distribution and overall thermal performance across the height of the window assembly.

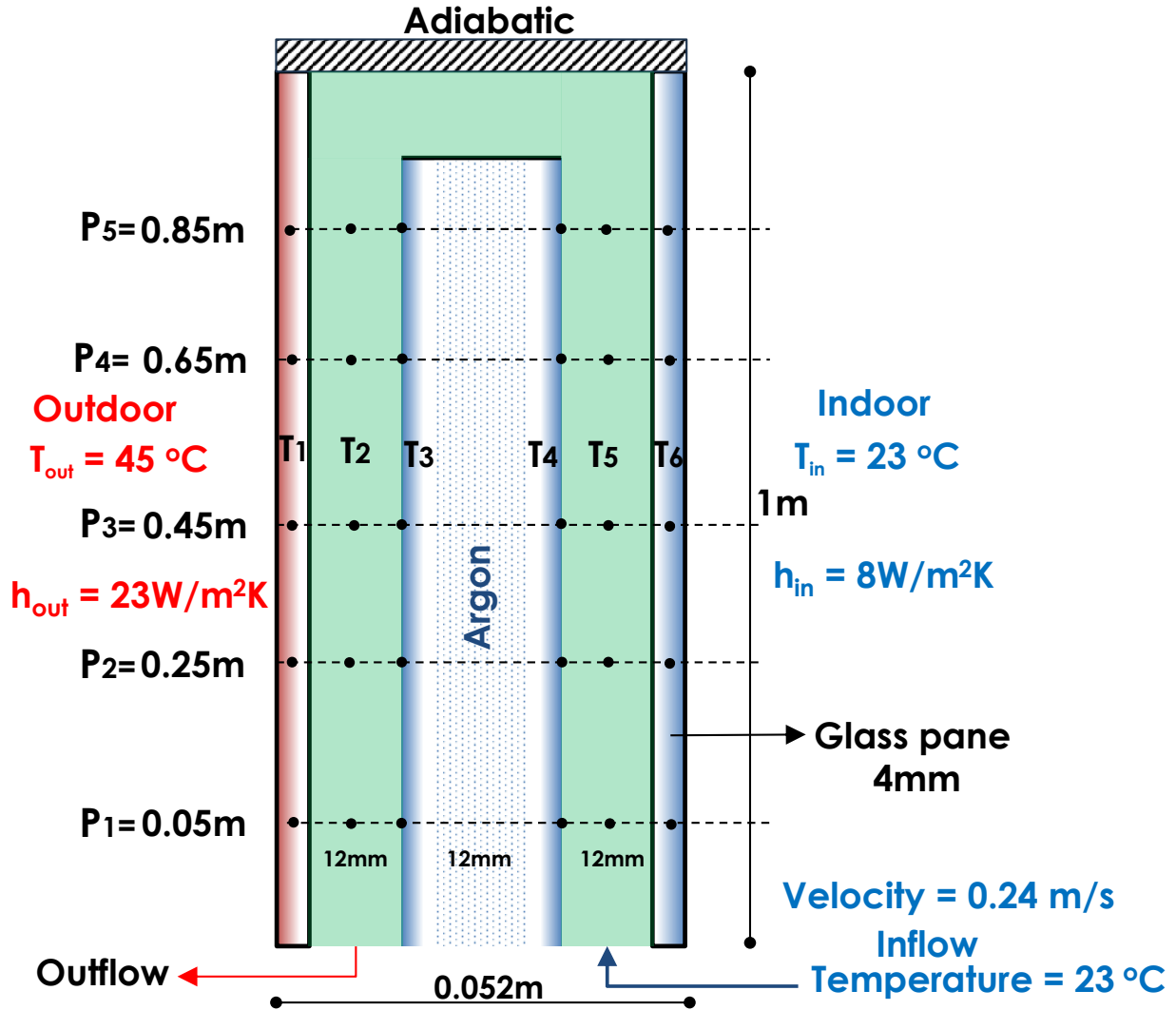


Figure 21. Geometry for the base case of EAW

Table 9 summarizes the critical geometric and thermal properties of the EAW system's base case. The window is 1 m high and has a total assembly thickness of 0.052 m, with each slot 12 mm wide. It features glass panes with a thickness of 4 mm and a thermal conductivity of 1 W/m·K. These specifications are the fundamental parameters for conducting a comparative analysis against alternative configurations, which will be discussed later in this study.

Table 9. Parameters for the EAWo

Height (m)	Assembly Thickness (m)	Glass Pane (m)	Slot size (m)
1	0.052	0.004	0.012
Named selection		Domain	
T ₁ T ₆		Solid (Glass)	
T ₂ T ₅		Fluid (Air)	
T ₃ T ₄		Surface (Glass)	

3.9 Geometries of various configurations for EAW alternatives

The circular, square, and triangular bars used in these configurations are polycarbonate. This transparent and lightweight material ensures minimal obstruction to the outside view while effectively enhancing airflow behavior and convective heat transfer.

Due to their optical clarity, these bars maintain the aesthetic and functional transparency of the Energy-Active Window (EAW) system, making them an ideal choice for architectural applications where visibility and energy efficiency are priorities. Additionally, polycarbonate's durability and resistance to thermal deformation ensure long-term stability and performance without compromising light transmission or external visibility.

3.10 Geometries of EAW system with circular bars configuration

Figure 22 shows alternate circular bar configurations that promote air mixing with glass surfaces to improve convective heat transfer efficiency in the EAW system. Table 10 describes each alternative.

Two or three 3mm-diameter bars were strategically inserted in the supply air slot, return air slot, or both to evaluate heat transfer and turbulence formation. These bars should disturb the thermal boundary layer along glazing surfaces, allowing airflow to interact with window panes and increasing heat absorption and dissipation.

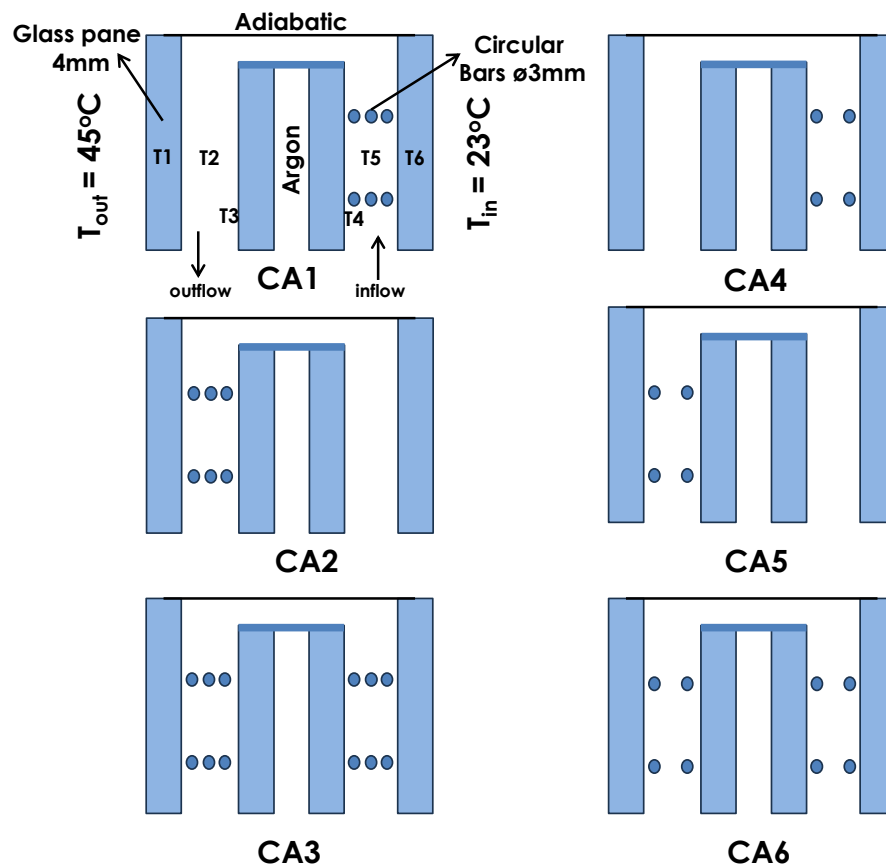


Figure 22. Schematic of circular bar alternatives

Table 10. Description of circular bar alternatives

Sr. No.	Description
CA1	3 bars of 7.07 mm ² at 0.1m c/c in inflow air slot only.
CA2	3 bars of 7.07 mm ² at 0.1m c/c in outflow air slot only.
CA3	3 bars of 7.07 mm ² at 0.1m c/c in both air slots.
CA4	2 bars of 7.07 mm ² at 0.1m c/c in inflow air slot only.
CA5	2 bars of 7.07 mm ² at 0.1m c/c in the outflow air slot.
CA6	2 bars of 7.07 mm ² at 0.1m c/c in both air slots.

Three bars in both slots (Alternative 3) provide the most turbulence, maximizing convective heat transfer, but they may also increase pressure drops, reducing system efficiency. Alternatives 4 and 5, with two bars in a single air slot, may reduce turbulence but increase convective heat transfer. Each arrangement must be carefully assessed to balance thermal performance and airflow resistance, as excessive turbulence may increase airflow energy consumption.

3.11 Geometries of EAW system with square bars configuration

Figure 23 demonstrates the airflow dynamics in the Energy-Active Window (EAW) system by strategically placing 9 mm² square bars in the supply or return air slots. Similar to circular bars, square bars block airflow, increase turbulence, and improve convective heat transfer efficiency by enhancing air-glass interaction.

Their ability to change flow pattern and heat transfer depends on bar shape. Square bars have a larger cross-sectional area (9 mm² vs. $\pi(3\text{mm})^2 = 7.07 \text{ mm}^2$ for circular bars). This

may improve flow disturbances and turbulence strength, breaking up thermal boundary layers on glazing surfaces and improving convective heat transfer.

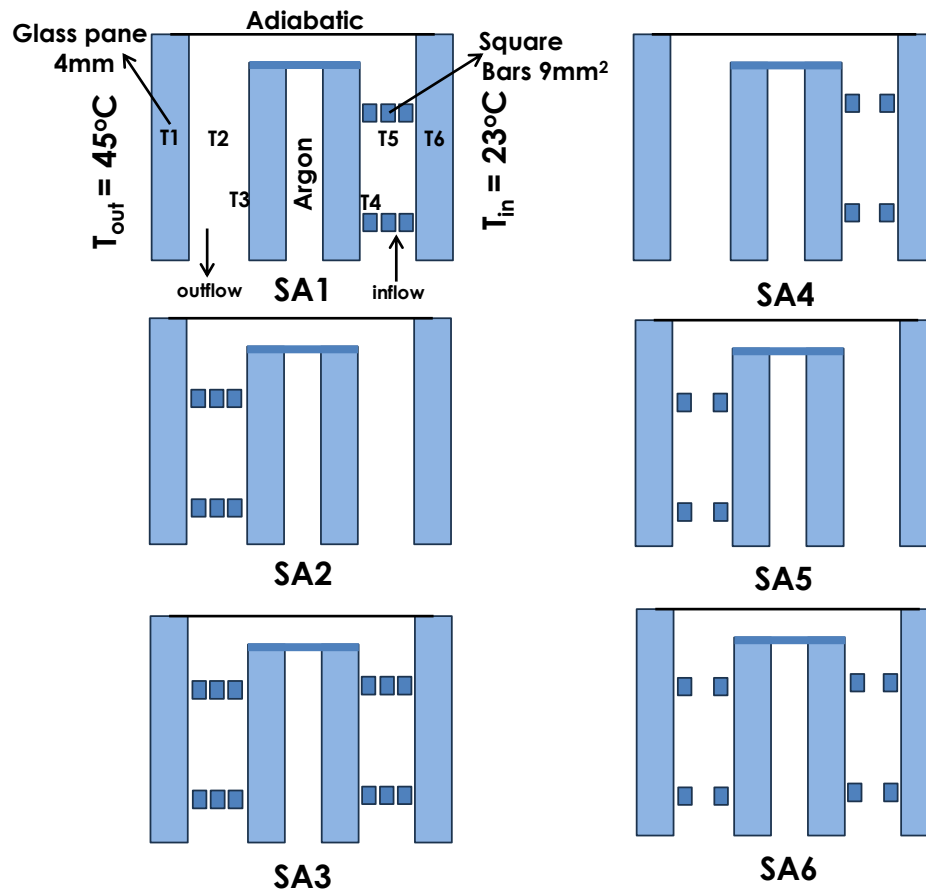


Figure 23. Schematic of square bar alternatives

The square bars' sharp edges provide localized flow separation and wake zones, which may increase air mixing and thermal interaction with window panes. This may help disperse heat more evenly, enhancing heat absorption and dissipation. Square bars can also create bigger pressure dips than circular bars, requiring more airflow energy to maintain velocity. While square bars generate more turbulence, they may also increase airflow resistance. The placement and amount of bars in each possibility affect system performance. Alternative 3, with three bars in both air slots, may produce maximum turbulence. In contrast,

Alternatives 4 and 5, with two bars in a single slot, increase air mixing moderately but have lower resistance, as presented in Table 11.

Table 11. Description of square bar alternatives

Sr. No.	Description
SA1	3 bars of 9 mm ² at 0.1m c/c in inflow air slot only.
SA2	3 bars of 9 mm ² at 0.1m c/c in outflow air slot only.
SA3	3 bars of 9 mm ² at 0.1m c/c in both air slots.
SA4	2 bars of 9 mm ² at 0.1m c/c in inflow air slot only.
SA5	2 bars of 9 mm ² at 0.1m c/c in outflow air slot.
SA6	2 bars of 9 mm ² at 0.1m c/c in both air slots.

The contrast between square and circular bars emphasizes compromise. Square bars may boost heat transfer by increasing turbulence and wake but also increase pressure losses, reducing airflow efficiency. Thus, they work best when convective heat transfer and airflow are balanced. This study will determine which bar configuration will improve heat transfer and aerodynamic performance more than the other, enabling more efficient Energy-Active Windows for sustainable building applications.

3.12 Geometries of the EAW system with triangular bar configuration

As shown in Figure 24, triangular bar configurations affect Energy-Active Window (EAW) airflow by strategically positioning turbulence-inducing bars in supply and return air slots and the related interpretation in Table 12. Triangular bars have the smallest cross-sectional area (4.5 mm²) compared to circular and square bars, affecting airflow and convective heat

transfer efficiency. These bars strengthen air mixing with glazing surfaces, generate turbulence, and break thermal boundary layers to promote heat absorption and dissipation. Triangular bars have less airflow resistance than circular and square bars due to their streamlined design and smaller cross-sectional area.

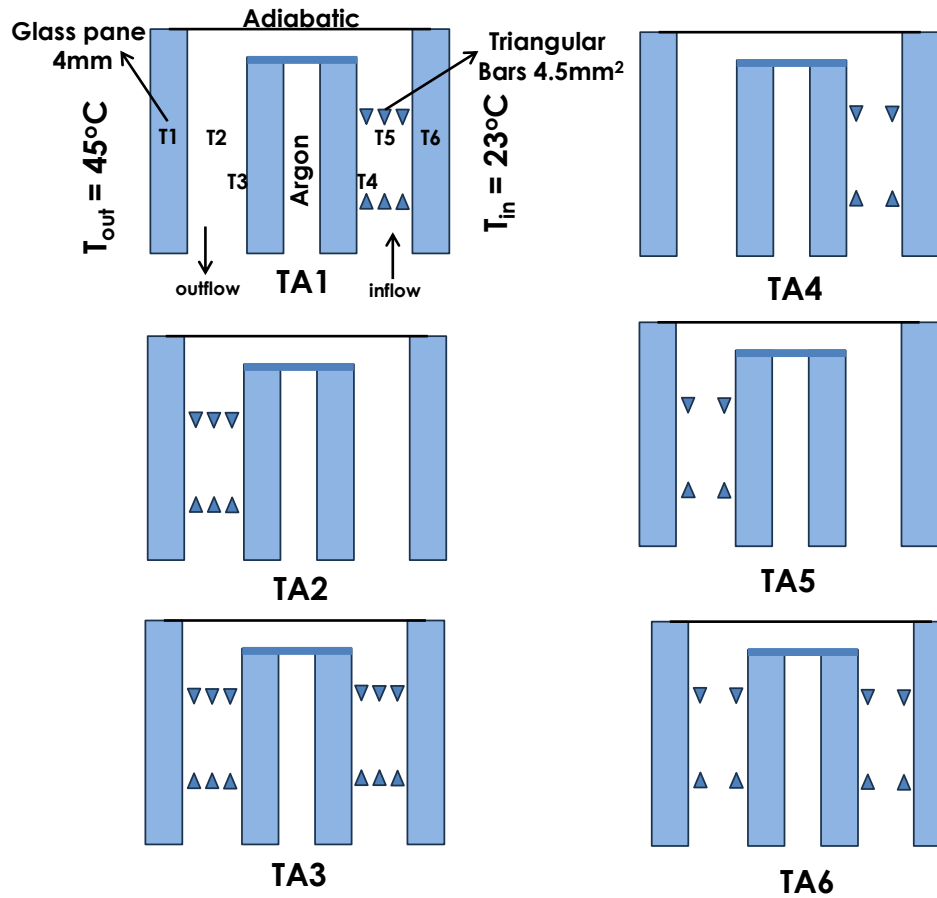


Figure 24. Schematic of triangular bar alternatives

With their sharp edges and larger (9 mm^2) blockage area, square bars cause the maximum turbulence and pressure drop, impacting airflow efficiency and energy consumption. Circular bars balance airflow resistance and mixing effectiveness with moderate turmoil due to their rounded shape and medium blockage area (7.07 mm^2). Sharp edges can still create localized turbulence and vortex shedding, but their reduced surface area reduces

resistance, making them more aerodynamic than square bars. Three bars in both air slots (Alternative 3) may have maximum turbulence and heat transmission.

Table 12. Description of triangular bar alternatives

Sr. No.	Description
TA1	3 bars of 4.5 mm ² at 0.1m c/c in inflow air slot only.
TA2	3 bars of 4.5 mm ² at 0.1m c/c in outflow air slot only.
TA3	3 bars of 4.5 mm ² at 0.1m c/c in both air slots.
TA4	2 bars of 4.5 mm ² at 0.1m c/c in inflow air slot only.
TA5	2 bars of 4.5 mm ² at 0.1m c/c in outflow air slot.
TA6	2 bars of 4.5 mm ² at 0.1m c/c in both air slots.

Square bars create the most turbulence, while triangular bars manage pressure and lose less. Two-bar layouts (Alternatives 4, 5, and 6) exhibit moderate turbulence; square bars may increase heat transfer, while triangular bars are more energy-efficient due to decreased obstruction. Heat transfer improvement and aerodynamic performance determine bar geometry. Square bars promote turbulence and heat transfer but increase pressure losses, circular bars moderate turbulence and efficiency, and triangular bars reduce airflow resistance and improve convective heat transfer through localized flow disturbances.

3.13 Geometry creation for EnergyPlus simulations

In the EnergyPlus simulations using DesignBuilder conducted for this study, the geometric characteristics of the model building were defined to ensure consistency with realistic architectural layouts and accurately represent energy performance. The simulated building

was modeled with a square shape and a floor-to-ceiling height of 3.5 meters, typical for modern residential or office spaces.

The total floor area was 100 m² (10 m × 10 m), providing a compact and manageable zone for evaluating thermal behaviors. The model incorporated a high window-to-wall ratio (WWR) of 85%, which is particularly relevant in assessing the influence of fenestration systems like the proposed Energy Active Window (EAW), as shown in Figure 25.

These geometric inputs provided the foundation for simulating airflow, heat transfer, and thermal comfort interaction within the building envelope, thereby supporting the comparative analysis of the EAW system against traditional window solutions under realistic spatial configurations.

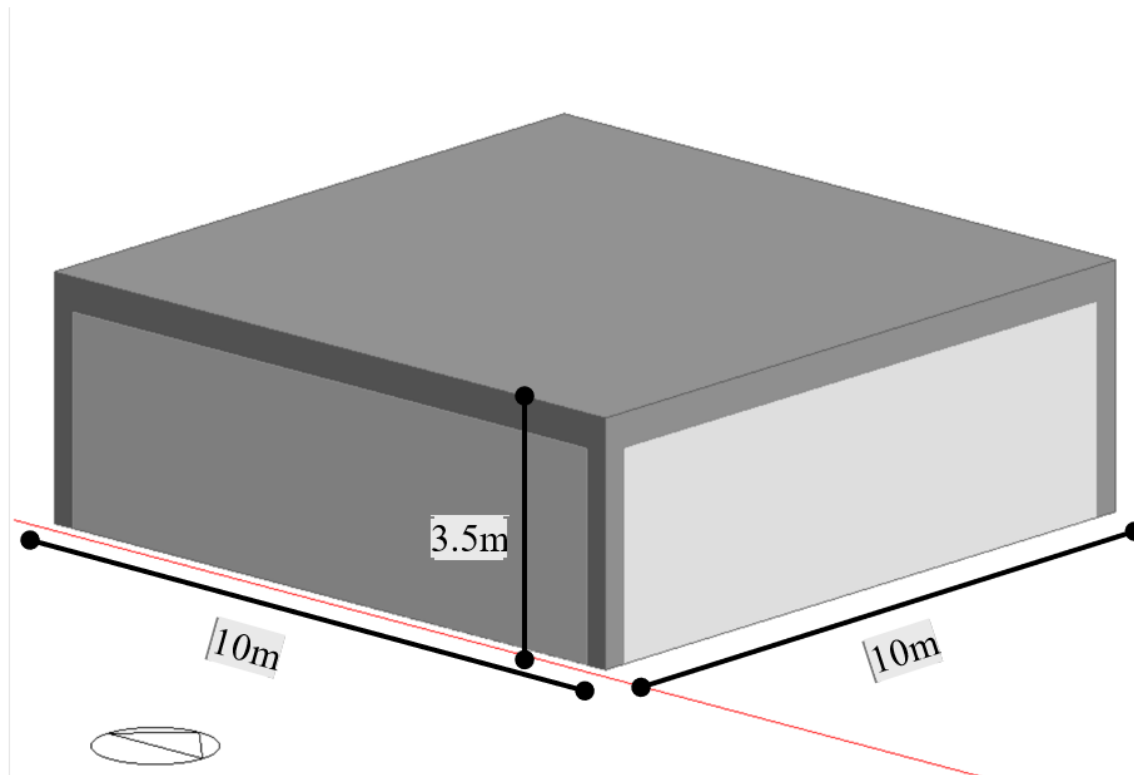


Figure 25. Geometric model for EnergyPlus simulations

3.14 Boundary conditions for CFD simulations

Boundary conditions for the present are presented in Table 13. The air enters the system at an inflow temperature of 23°C and a velocity of 0.24 m/s. The indoor convective heat transfer coefficient (h_{in}) is set at 8 W/m².K [72], reflecting the controlled and relatively stable indoor environmental conditions. In contrast, the outdoor convective heat transfer coefficient (h_{out}) is established at 23 W/m².K [72] to represent realistic external environmental influences. The indoor temperature (T_{in}) is maintained at a constant 23°C to ensure stable and comfortable indoor conditions. Meanwhile, the outdoor temperature (T_{out}) is set at 45°C, simulating external heating conditions such as direct exposure to solar radiation, providing a realistic thermal gradient across the system.

Table 13. Parameters and boundary conditions for the present study

Height (m)	Assembly Thickness (m)	Glass Pane (mm)	Thermal conductivity (glass) (W/m.K)	T_{out} (°C)	T_{in} (°C)	h_{in} (W/m ² .K)	h_{out} (W/m ² .K)	Velocity (m/s)
1	0.052	4	1	45	23	8	23	0.24

Table 14 demonstrates further detailed boundary conditions employed in the simulation, carefully selected to ensure accuracy, numerical stability, and computational efficiency from [73]. The laminar model was chosen for the simulation due to the relatively low Reynolds number within the window air slots, where airflow remains predominantly smooth and non-turbulent. The hex-dominant (structured) mesh type was implemented to provide a well-organized computational grid, minimizing numerical diffusion and ensuring better convergence with reduced computational effort.

The domain size was set at 0.052 m x 1 m (width x height) to capture the heat transfer and airflow characteristics within a representative section of the energy-active window (EAW) system while keeping computational costs manageable. A second-order upwind discretization scheme was applied to improve the accuracy of convection-dominated flow equations, reducing numerical errors and enhancing the precision of results. The simulation was conducted under steady-state conditions, assuming that the temperature distribution and airflow patterns do not change over time, which is valid for assessing long-term thermal performance.

To ensure realistic boundary conditions, heat transfer through the frame was considered adiabatic, implying that no heat exchange occurs through the window frame, thereby isolating the effect of airflow and glazing configurations. The air density was set at 1.205 kg/m³, corresponding to standard atmospheric conditions. The wall motion was put to stationary, indicating that the window surfaces do not move, thus simplifying the simulation and focusing on convective heat transfer effects.

At the outlet boundary, a relative static pressure of zero was applied, ensuring a smooth exit of airflow without artificial pressure buildup. The convergence criteria for continuity, velocity (x and y directions), and energy equations were set to 10^{-6} [73], ensuring high accuracy in iterative solutions while reducing the residual error to an acceptable level. The COUPLED algorithm for pressure-velocity coupling was used to improve numerical stability and achieve faster convergence by solving pressure and velocity simultaneously rather than sequentially.

The computational grid consisted of an average of 0.2 million cells, providing sufficient resolution to capture temperature gradients and velocity variations without excessive computational demand. The velocity specification method was set as magnitude, normal to boundary, ensuring that airflow enters perpendicular to the inlet surface. The velocity varied as per iterations, meaning it was dynamically adjusted based on solver calculations to capture the natural variations in airflow behavior. Finally, a pressure outlet boundary condition was applied to allow air to exit freely while maintaining a realistic pressure gradient.

Moreover, pseudo-time explicit relaxation factors play a crucial role in stabilizing the numerical solution and enhancing convergence efficiency in the simulation setup. These relaxation factors control how much the newly computed variable values influence the next iteration, ensuring smooth progression towards a stable solution. For this study, pressure and momentum relaxation factors were set to 0.5, the body forces relaxation factor to 1, and the energy relaxation factor to 0.75.

Setting the pressure and momentum relaxation factors at 0.5 helps to moderate fluctuations in velocity and pressure fields, particularly in cases where flow conditions exhibit strong coupling between pressure and velocity. A lower value prevents excessive oscillations, ensuring a steady and stable convergence path while avoiding divergence. However, it is not set too low, as excessively small values would slow down the rate of convergence.

The body forces relaxation factor of 1 allows the solver to fully apply gravitational and other external forces in each iteration, ensuring that buoyancy-driven effects and natural convection are accurately captured without artificial damping. This is particularly relevant

in airflow simulations involving temperature gradients, where buoyancy forces influence the overall flow field. The energy relaxation factor of 0.75 is slightly higher than that for momentum and pressure, allowing the solver to adjust temperature calculations efficiently without causing abrupt changes that could destabilize the solution. Since energy equations are typically slower to converge due to their nonlinear nature, an optimized value of 0.75 strikes a balance between maintaining numerical stability and achieving reasonable computational efficiency.

It is crucial to narrate the governing equations coupled with appropriate boundary conditions to solve fluid flow and heat transfer problems:

Continuity equation (Mass conservation)

$$\nabla \cdot \rho \mathbf{v} = 0 \quad (16)$$

Momentum equation (Navier-Stokes)

$$\nabla \cdot (\rho \mathbf{v} \mathbf{v}) = -\nabla p + \nabla \cdot \boldsymbol{\tau} + \rho \mathbf{f} \quad (17)$$

Energy equation (Thermal energy conservation)

$$\rho c_p \mathbf{v} \cdot \nabla T = \nabla \cdot (k \nabla T) + \Phi + q' \quad (18)$$

The governing equations used in this study include the continuity equation, momentum equations, and energy equation, which together describe the fundamental principles of fluid flow and heat transfer within the energy-active window (EAW) system. The continuity equation (16) ensures the conservation of mass, stating that the net mass flux entering and

leaving any control volume remains balanced. Since air is treated as an incompressible fluid, this equation simplifies the divergence of velocity being zero, meaning that the airflow remains consistent throughout the domain without accumulation or loss of mass.

The momentum equations 17, derived from Newton's second law, governs the movement of air as it flows through the window slots. These equations account for pressure gradients, which drive the airflow, viscous forces, which introduce shear stress due to internal friction, and external forces that may influence motion. Given the laminar flow conditions assumed in this study, the equations remain simplified while still capturing the velocity distribution across the window system. The airflow velocity affects heat transfer efficiency by modifying residence time, which plays a crucial role in cooling the window panes.

The energy equation 18 ensures thermal energy conservation by accounting for different heat transfer mechanisms. It considers convective heat transfer, where energy is transported by the moving air, thermal conduction, where heat diffuses due to temperature gradients, and viscous dissipation, which represents energy conversion due to fluid motion. In this study, convection and conduction are the dominant modes of heat exchange, with air movement influencing how heat is extracted from the window panes. The interaction between airflow and window surfaces determines the system's effectiveness in preventing excessive heat buildup, thereby improving indoor thermal conditions. These equations collectively enable an accurate numerical representation of the heat and airflow behavior in the EAW system, allowing for the evaluation of different airflow configurations and their impact on energy efficiency.

This well-structured approach to boundary conditions ensures that the simulation accurately captures the EAW system's thermal and aerodynamic behaviour while optimising computational efficiency.

Table 14. Boundary conditions settings in CFD

Sr. No.	Boundary	Settings
1	Model	Laminar
2	Mesh Type	Hex-dominant (structured)
3	Domain Size	0.052m x 1m (w x h)
4	Discretization Scheme	Second-order upwind
5	Time	Steady state simulation
6	Heat transfer through the frame	Adiabatic
7	Air density	1.205
8	Wall Motion	Stationary wall
9	Outlet	Relative static pressure is zero
10	Convergence Criteria	x, y, energy, continuity = 10^{-6}
11	Algorithm (pressure velocity coupling)	COUPLED
12	Total number of cells (Average)	0.2 million
13	Velocity specification method	Magnitude, normal to boundary
14	Velocity	Varies as per iterations
15	Outlet boundary condition	Pressure outlet

3.15 Mesh independence

A mesh independence study is a crucial step in computational simulations to ensure that the mesh resolution does not significantly influence numerical results. This process involves refining the mesh size progressively and observing its impact on key simulation parameters, such as outflow temperature in the case of the proposed energy-active window system. The goal is to identify the finest mesh size beyond which further refinement yields negligible changes in results, thereby optimizing computational efficiency without

sacrificing accuracy. A highly refined mesh improves the resolution of numerical solutions but also increases computational cost, requiring more processing power and memory.

On the other hand, an excessively coarse mesh may introduce discretization errors, leading to inaccurate results. Therefore, selecting an appropriate mesh size balances accuracy with computational feasibility. The data presented indicates that the outflow temperature remains relatively stable as the mesh element size decreases from 0.0008 m to 0.0003 m, as shown in Figure 26. The variation in outflow temperature is minimal, ranging only between 38.811°C and 38.814°C. Consequently, the percentage error in return air temperature remains extremely small, with a maximum observed deviation of just 0.00258%. These results suggest that refining the mesh beyond an element size of 0.0005 m does not yield significant accuracy improvements.

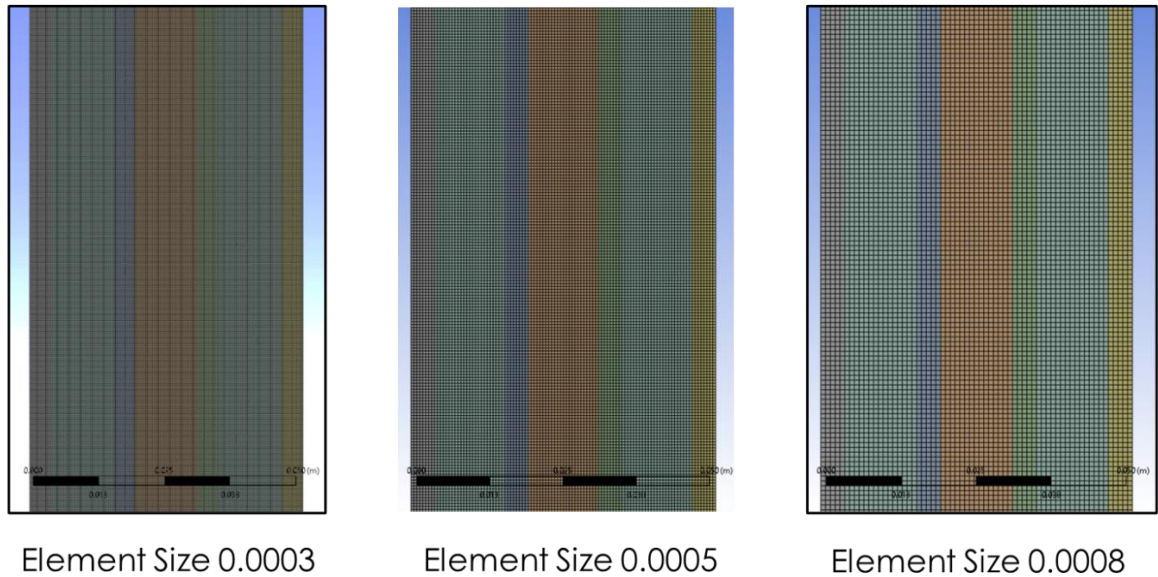


Figure 26. Mesh size visualization

For instance, reducing the element size from 0.0005 m to 0.0004 m results in no measurable change in outflow temperature, and further refinement to 0.0003 m similarly offers no

appreciable gains in accuracy. This confirms that the solution has reached a mesh-independent state, and additional mesh refinement would only increase computational cost without enhancing result reliability.

Given these computational constraints and accuracy considerations, an element size of 0.0005 m was chosen for the final simulation, as shown in Figure 27. This selection offers a minimal error deviation, with the outflow temperature (38.814°C) nearly identical to those obtained using finer meshes, ensuring sufficient accuracy.

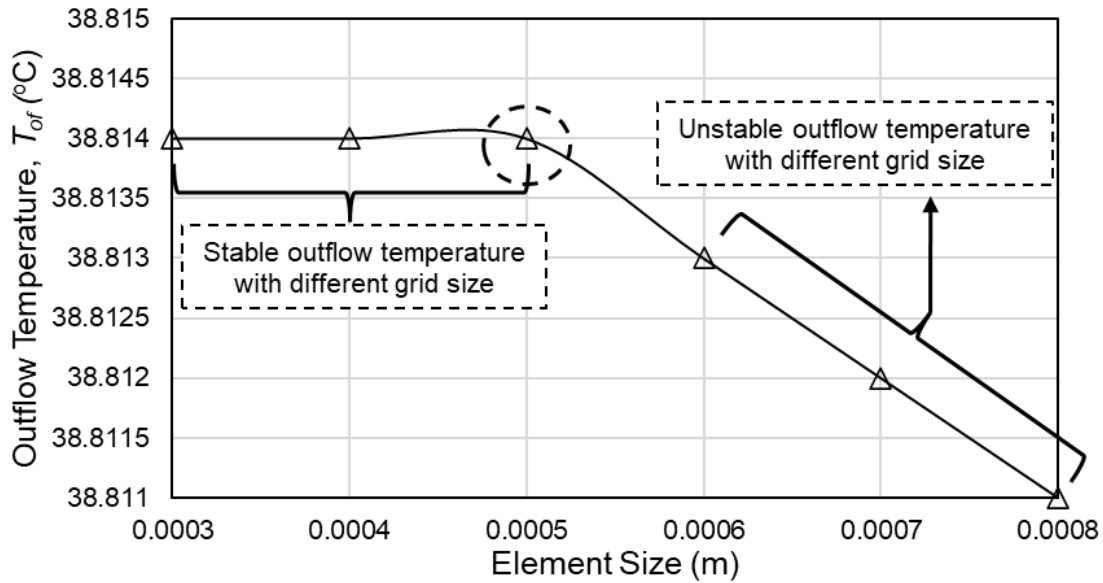


Figure 27. Mesh independence study

Additionally, this element size provides optimal computational efficiency, requiring only 208,000 elements—significantly fewer than the 325,000 or more elements needed for smaller mesh sizes. Thus, computation time and memory usage are reduced while reliable results are maintained. Selecting an element size of 0.0005 m ensures an effective balance between computational feasibility and numerical accuracy. This is essential when

computational resources are limited, thereby preserving the integrity of the thermal analysis in the energy-active window (EAW) system, as shown in Table 15 below.

Table 15. Mesh independence based on outflow temperature

Element Size	No. of Nodes	No. of Elements	Outflow temp. (°C)	%Error outflow temp.
0.0003	596618	573208	38.814	0.00000
0.0004	342565	325000	38.814	0.00000
0.0005	222054	208000	38.814	0.00258
0.0006	158288	146609	38.813	0.00258
0.0007	117170	107130	38.812	0.00258
0.0008	90036	81250	38.811	-

3.16 Boundary conditions for EnergyPlus simulations

A detailed EnergyPlus (DesignBuilder) simulation was conducted for a representative residential dwelling with an integrated kitchen to evaluate the thermal performance and energy consumption of an energy-active window system. The model building is in Dhahran (26.27° N latitude, 50.15° E longitude), reflecting the hot and arid climate typical of the Eastern Province of Saudi Arabia. The structure is square-shaped with a floor area of 100 m² (10 m × 10 m) and a floor-to-ceiling height of 3.5 meters. The building orientation is set at 245° from the true north, and the window-to-wall ratio (WWR) is set at a high 85% to emphasize the influence of fenestration systems on thermal loads, as shown in Table 16. However, this glazing percentage is only for theoretical application; for the practical applications, the modules (EAW units) will be installed because each unit contains

integrated geometric configurations and a fan unit for forced convection to enhance its performance in terms of energy efficiency and thermal performance and comfort.

The simulation assumes an air infiltration rate of 0.3 air changes per hour (ACH) and an occupant density of 0.0215 persons per square meter. Each occupant contributes a metabolic rate of 117 W, and clothing insulation levels were varied seasonally: 0.5 clo for summer and 1.0 clo for winter to reflect adaptive comfort behavior.

The building envelope consists of walls and a roof with U-values of 0.351 W/m²·K and 0.346 W/m²·K, respectively. The U-values of the windows were defined based on the glazing system being evaluated: single glazing (5.8 W/m²·K), double glazing (3.16 W/m²·K), and triple glazing (2.2 W/m²·K). The corresponding solar heat gain coefficients (SHGC) are 0.86 for single and triple glazing and 0.76 for double glazing. The U-values for energy-active windows were modeled according to the performance characteristics detailed in the supplementary tables of the study.

Table 16. Boundary conditions used in the EnergyPlus simulation

Parameter	Model Description
Location	Dhahran, Saudi Arabia (26.27° N, 50.15° E)
Building Orientation	Positioned at 245° from geographical North
Layout Shape	Square configuration
Ceiling Height	3.5 meters
Total Floor Area	100 square meters (10 m × 10 m)
Window-to-Wall Ratio	85%
Infiltration Rate	0.3 air changes per hour (ACH)

Parameter	Model Description
Occupant Density	0.0215 persons per square meter
Internal Heat Gains	117 watts per person
Clothing Insulation Levels	0.5 clo (summer); 1 clo (winter)
Wall Thermal Transmittance	0.351 W/m ² ·K
Roof Thermal Transmittance	0.346 W/m ² ·K
Window U-Values	Case-specific (see individual window specifications below)
HVAC System Configuration	Split unit with independent mechanical ventilation
Ventilation Rate	3 ACH via mechanical system
Supply Air Temperature	12°C
System Operation Mode	Operates continuously
Cooling Setpoint (Summer)	24°C
Lighting Power Density	5 W/m ² with target illumination of 100 lux
Lighting Type	Compact fluorescent lighting (CFL)
Heating Setpoints	Active heating: 18°C; Setback: 12°C
Cooling Setpoints	Active cooling: 21°C; Setback: 28°C

The HVAC system modeled is a split system with separate mechanical ventilation set to 3 ACH, delivering supply air at 12°C under continuous operation. Seasonal setpoint temperatures were assigned, with a summer cooling setpoint of 24°C. The heating setpoint temperature was set to 18°C with a setback temperature of 12°C, while the cooling setback temperature was configured at 28°C and the primary cooling temperature at 21°C. These

values were chosen to balance occupant comfort with energy conservation under various operating conditions. Internal lighting loads were also modeled with a lighting power density of 5 W/m² under a constant illuminance level of 100 lux, employing fluorescent compact lighting (CFL) as the standard light source. These boundary conditions form the baseline for comparative energy performance simulations across conventional and advanced window systems, providing a robust framework to assess the potential energy savings and thermal comfort benefits offered by the energy-active window configuration.

CHAPTER 4

RESULTS & DISCUSSION

This chapter presents and analyzes the results obtained from computational simulations conducted on various window configurations, including conventional double and triple glazing, a base-case Energy Active Window (EAW) system without airflow elements, and multiple proposed EAW alternatives featuring airflow elements of square, circular, and triangular geometries. The findings systematically address thermal performance, aerodynamic behavior, and thermal comfort metrics, supported by comprehensive validation through CFD and EnergyPlus simulations. Each alternative has been critically assessed against the base case to highlight improvements or shortcomings, focusing on factors such as air temperature distribution, heat transfer efficiency, velocity impacts, and occupant thermal comfort, thus providing valuable insights into optimizing window systems for enhanced building energy performance.

4.1 Base case model for EAW system

The base case model for the Energy Active Window (EAW) system, characterized by an absence of airflow elements, was analyzed to determine the impact of air velocity on its thermal performance. As shown in Table 17, varying the velocity from 0.24 m/s to 0.57 m/s significantly influences the outflow temperature.

Table 17. Inlet velocity and outflow temperature relationship for EAWo

Inlet velocity (m/s)	Outflow Temperature (°C)
0.24	38.81
0.33	37.87
0.41	36.98
0.49	36.14
0.57	35.36

At the lowest velocity (0.24 m/s), the system achieves the highest outflow temperature of 38.81°C, indicating more effective heat absorption due to increased air residence time. Conversely, as velocity increases, the outflow temperature progressively decreases, reaching 35.36°C at 0.57 m/s. This demonstrates that higher air velocities reduce the residence time within the window cavity, thus limiting heat uptake from the glazing surfaces and resulting in lower outflow temperatures, as shown in Figure 28. This fundamental relationship between velocity and thermal performance provides a baseline for comparison with other proposed configurations featuring airflow elements.

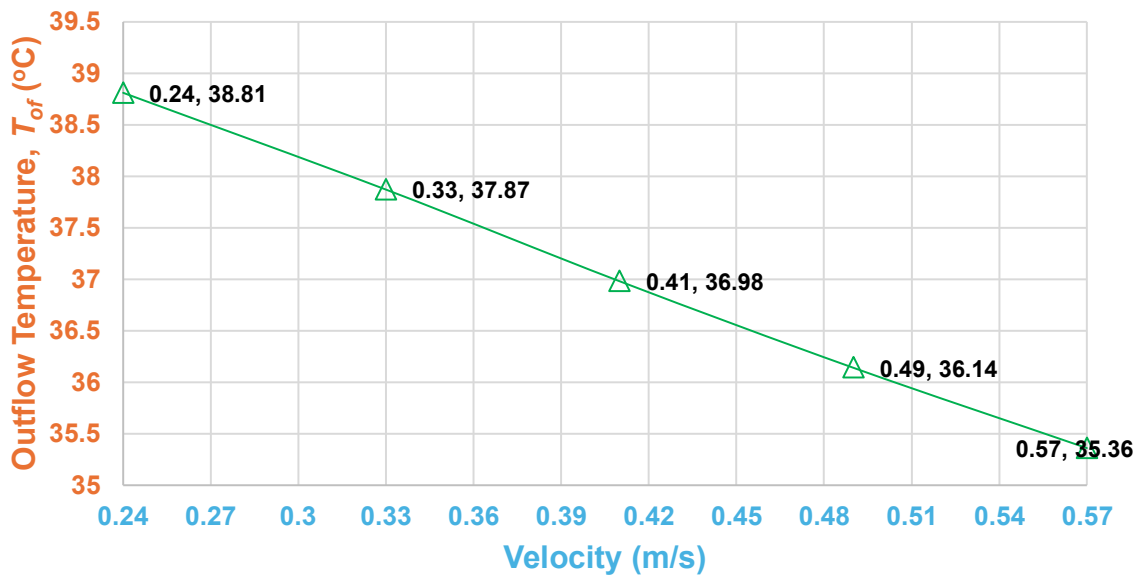


Figure 28. Impact of velocity on outflow temperature in EAWo

The observed gradual decrease in outflow temperature with increasing velocity confirms that a balance must be maintained between the airflow rate and thermal absorption efficiency. At 0.24 m/s, the system achieves a stable and satisfactory thermal exchange, making it an ideal operating condition for the study.

4.2 Impact of velocity on temperature distribution in EAWo

The given Table 19 (Appendix A) and Figure 29 demonstrate a detailed temperature distribution within the Energy Active Window (EAW) base case at varying airflow velocities from 0.24 m/s to 0.57 m/s, reflecting the influence of airflow velocity on heat transfer along the window height and cross-section.

At the lowest velocity of 0.24 m/s, due to prolonged air residence time, significant heat absorption occurs. At the lowest section ($P_1 = 0.05$ m), the outer pane temperature (T_1) is highest at 42.28°C, indicating substantial heat transfer from the external environment (45°C), while the outflow air slot (T_2) closely follows at 38.63°C. Moving upwards to P_5 (0.85 m), these temperatures notably decrease to 40.45°C (T_1) and 31.1°C (T_2), clearly indicating the upward flow of air absorbing heat progressively. Temperature consistently decreases inward across the window's cross-section, from T_1 (outer glazing) to T_6 (inner glazing), reflecting efficient thermal transfer towards the interior. The resulting average temperature difference (ΔT) between outer (T_1) and inner (T_6) panes is 15.964°C, confirming effective heat transfer at a lower velocity.

When velocity increases slightly to 0.33 m/s, the temperature distribution remains similar but with marginally reduced heat absorption, as indicated by a lower outflow temperature

of 37.86°C. At P₁, T₁ drops slightly to 41.92°C, with T₂ decreasing more significantly to 37.31°C. Higher up at P₅, the outer pane (T₁) further decreases to 39.89°C, while the outflow air temperature (T₂) reduces noticeably to 29.34°C, reflecting reduced residence time and, thus, reduced heat uptake. The overall average temperature difference remains nearly consistent at 15.960°C, suggesting stable but slightly diminished heat transfer efficiency compared to the 0.24 m/s scenario.

At 0.41 m/s, the impact of further increased velocity becomes evident, with the return air temperature dropping further to 37.10°C. At P₁, T₁ slightly reduces to 41.6°C, while T₂ notably decreases to 36.11°C, signifying that rapid airflow restricts heat absorption. The uppermost point (P₅) shows further reduction, with T₁ at 39.51°C and T₂ dropping significantly to 28.21°C. This indicates a weaker temperature gradient at higher elevations due to decreased residence time. The average ΔT slightly decreases to 15.904°C, indicating lower overall heat retention.

With an increased velocity of 0.49 m/s, the return air temperature further drops to 36.45°C, clearly reflecting the diminishing effect of increased airflow. At P₁, the outer glazing temperature (T₁) reduces to 41.3°C and T₂ to 34.98°C. At P₅, T₁ and T₂ decrease to 39.2°C and 27.37°C, respectively. The overall temperature distribution indicates reduced heat transfer effectiveness along both height and cross-section, with the average ΔT falling to 15.82°C.

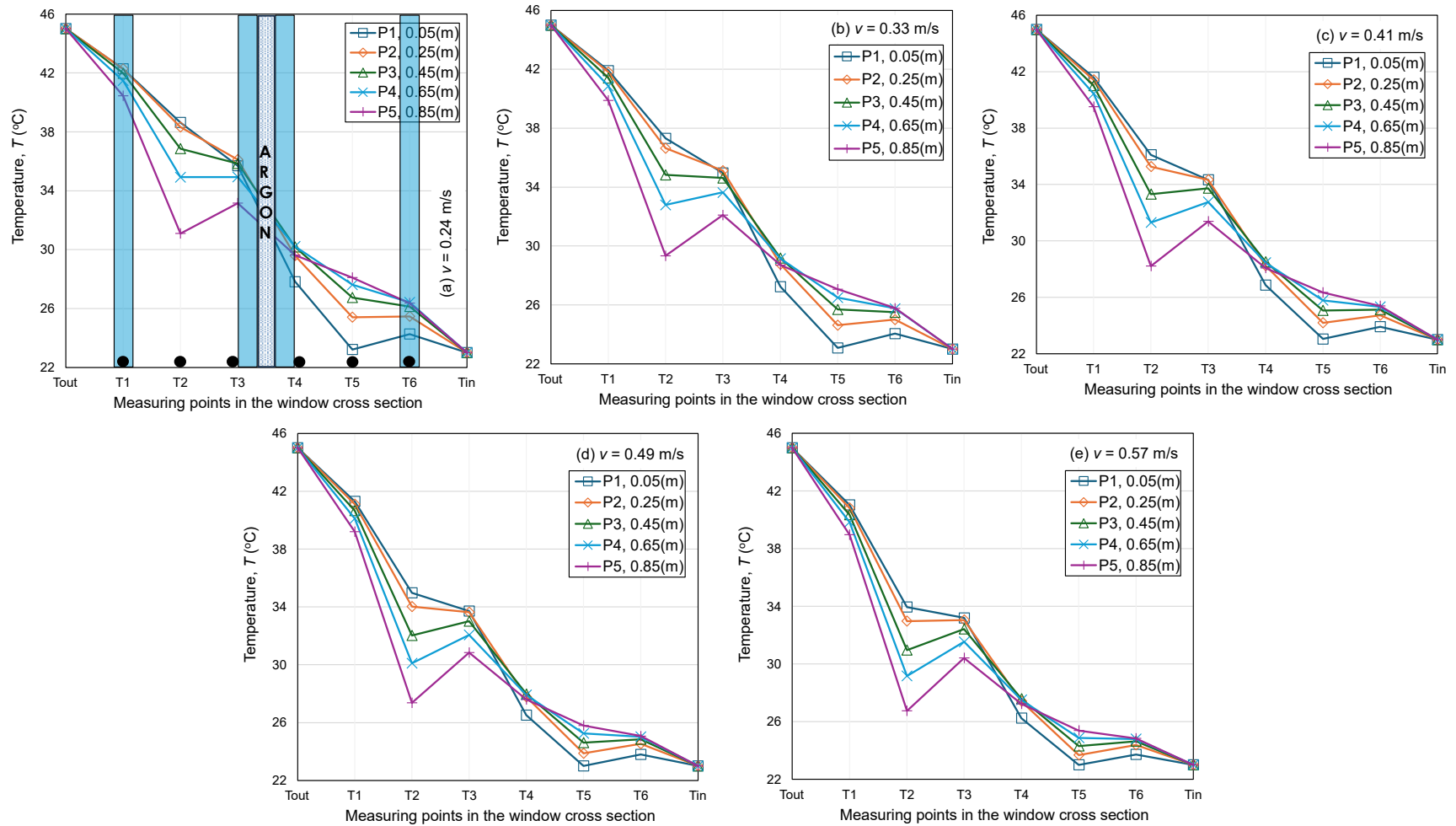


Figure 29. Temperature distribution along the window cross-section at a velocity of a) 0.24 m/s, b) 0.33 m/s, c) 0.41 m/s, d) 0.49 m/s, e) 0.57 m/s

Finally, the lowest heat retention occurs at the highest velocity of 0.57 m/s, evidenced by the lowest return air temperature of 35.36°C. At P_1 , T_1 and T_2 reduce to 41.03°C and 33.94°C, respectively, reflecting significantly lower heat absorption due to rapid airflow. At the top position, P_5 , temperatures further decrease, with T_1 at 38.95°C and T_2 at 26.73°C, indicating limited heat uptake by the rapidly moving air. Consequently, the average ΔT across the window drops to 15.73°C, underscoring that higher velocities substantially reduce the EAW system's thermal effectiveness by shortening air residence time, thus lowering overall heat transfer efficiency.

This comprehensive analysis highlights that lower velocities significantly enhance heat absorption and thermal efficiency within the EAW, while higher velocities, though increasing the airflow rate, result in reduced heat uptake and lower temperature gradients due to shorter residence times.

4.3 Integration of various geometric configurations in EAW

This section presents the results of integrating various geometric configurations, square, circular, and triangular bars, into the Energy Active Window (EAW) system. As indicated by prior literature, the rationale for selecting these particular shapes stems from their distinct aerodynamic properties and effectiveness in heat transfer enhancement. Square bars typically generate structured airflow patterns that promote effective heat absorption, circular bars are favored for minimal airflow obstruction due to their streamlined profile, and triangular bars enhance turbulence and mixing due to their sharp edges, facilitating improved convective heat transfer. By systematically evaluating these configurations, this

study aims to identify the most thermally efficient geometry to optimize airflow and heat uptake within the EAW system.

4.3.1 Integration of circular bars and its temperature distribution in the EAW system

The given data in Table 20 (Appendix A) thoroughly depicts the thermal performance of six circular bar configurations integrated into the Energy-Active Window (EAW). Each configuration is evaluated at specific positions along the height (P_1 at 0.05 m through P_5 at 0.85 m) and across cross-sectional points (T_1 – T_6), where T_1 and T_6 represent the outermost (exterior) and innermost (interior) panes, respectively.

In contrast, T_2 and T_5 represent the airflow outflow and inflow slots, as shown in Figure 30. Among all configurations, Alternative 2 demonstrates the most effective thermal performance. It achieves the highest outflow temperature (39.00°C) and a maximum average temperature difference ($\Delta T=16.042^\circ\text{C}$), reflecting its superior capacity to absorb and transfer heat effectively from the external environment to the interior.

Examining Alternative 2 closely, temperatures at point P_1 near the bottom exhibit the greatest heat absorption, with T_1 at 42.39°C and T_2 at 38.87°C, indicating a significant amount of heat transferred into the airflow.

Moving upward along the window height (toward P_5), temperatures decrease progressively (T_1 at 40.35°C and T_2 at 31.1°C), demonstrating effective thermal uptake as the air moves upward and absorbs heat before exiting. Similarly, across the cross-section from the external pane (T_1) to the internal pane (T_6), a consistent decrease in temperature confirms

efficient heat dissipation through each intermediate layer (T_3 and T_4 at intermediate panes), maintaining stable indoor glazing temperatures and a controlled indoor environment.

Alternatives 1 and 3 closely follow Alternative 2 in terms of performance, although slightly less effective. Alternative 1 yields an outflow temperature of 38.78°C and an average ΔT of 15.958°C , while Alternative 3 achieves 38.96°C and a ΔT of 16.022°C . These alternatives also show a strong vertical temperature gradient, with higher heat absorption at lower positions (P_1 : $T_1=42.29^\circ\text{C}$ and $T_2=38.86^\circ\text{C}$ for Alt. 1, $T_1=42.38^\circ\text{C}$ and $T_2=39.15^\circ\text{C}$ for Alt. 3), gradually decreasing toward the upper region (P_5). However, they exhibit slightly reduced heat retention and air-to-pane heat transfer effectiveness compared to Alternative 2.

Alternatives 4, 5, and 6 perform comparatively lower. Alternative 4, with an outflow temperature of 38.82°C and $\Delta T=15.928^\circ\text{C}$, shows slightly diminished performance, indicating less effective vertical and cross-sectional heat transfer. Alternative 5, exhibiting the lowest outflow temperature (38.76°C) and a reduced ΔT of 15.910°C , further highlights limited heat absorption, especially at upper window positions (P_5 : $T_2=31.5^\circ\text{C}$), likely due to reduced residence time or inefficient mixing patterns. Similarly, Alternative 6 (outflow temperature= 38.78°C , $\Delta T=15.886^\circ\text{C}$) also reveals lower heat uptake efficiency, particularly at upper cross-section points.

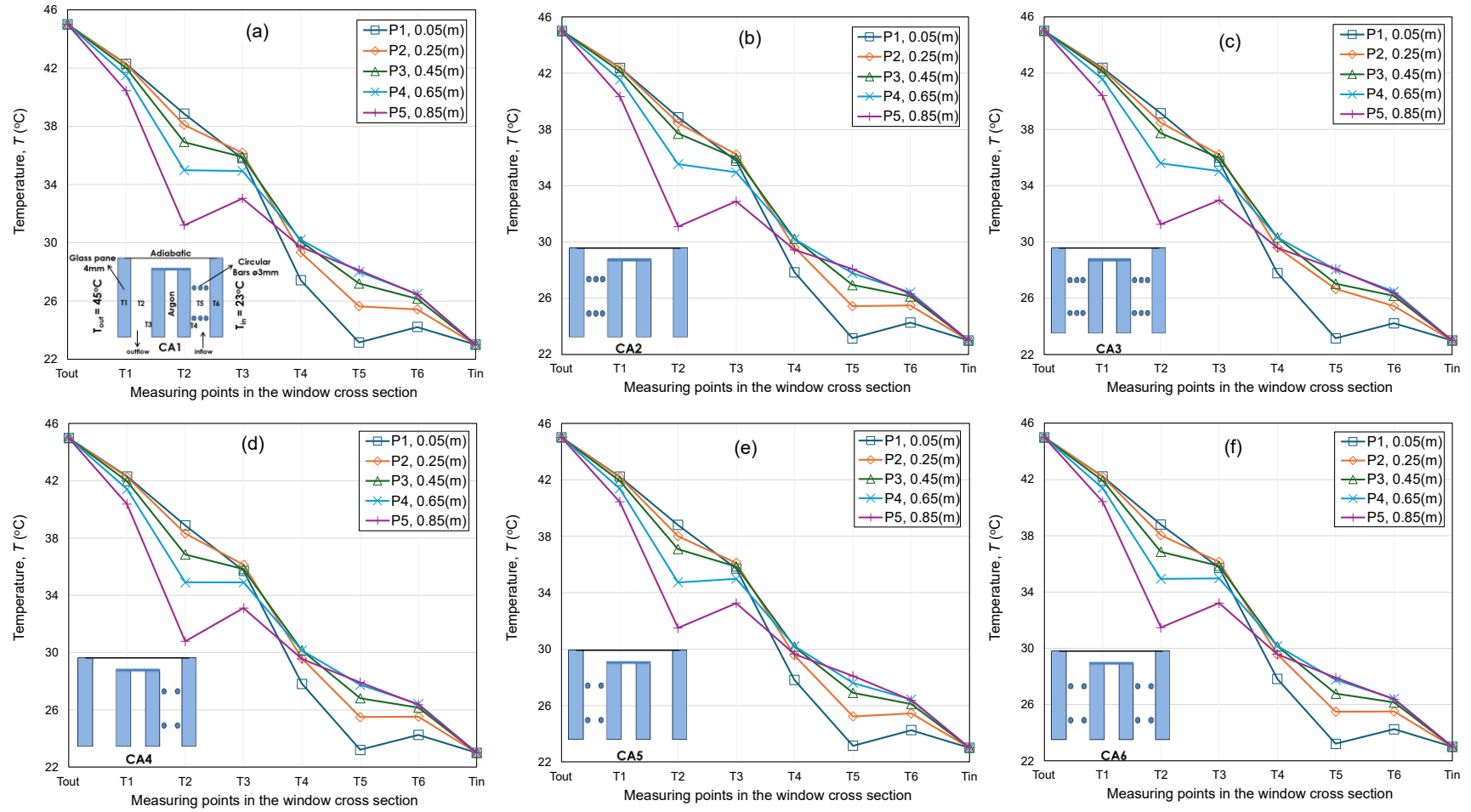


Figure 30. Temperature distribution along the window cross-section for a) Alternative 1 (CA₁), b) Alternative 2 (CA₂), c) Alternative 3 (CA₃), d) Alternative 4 (CA₄), e) Alternative 5 (CA₅), f) Alternative 6 (CA₆)

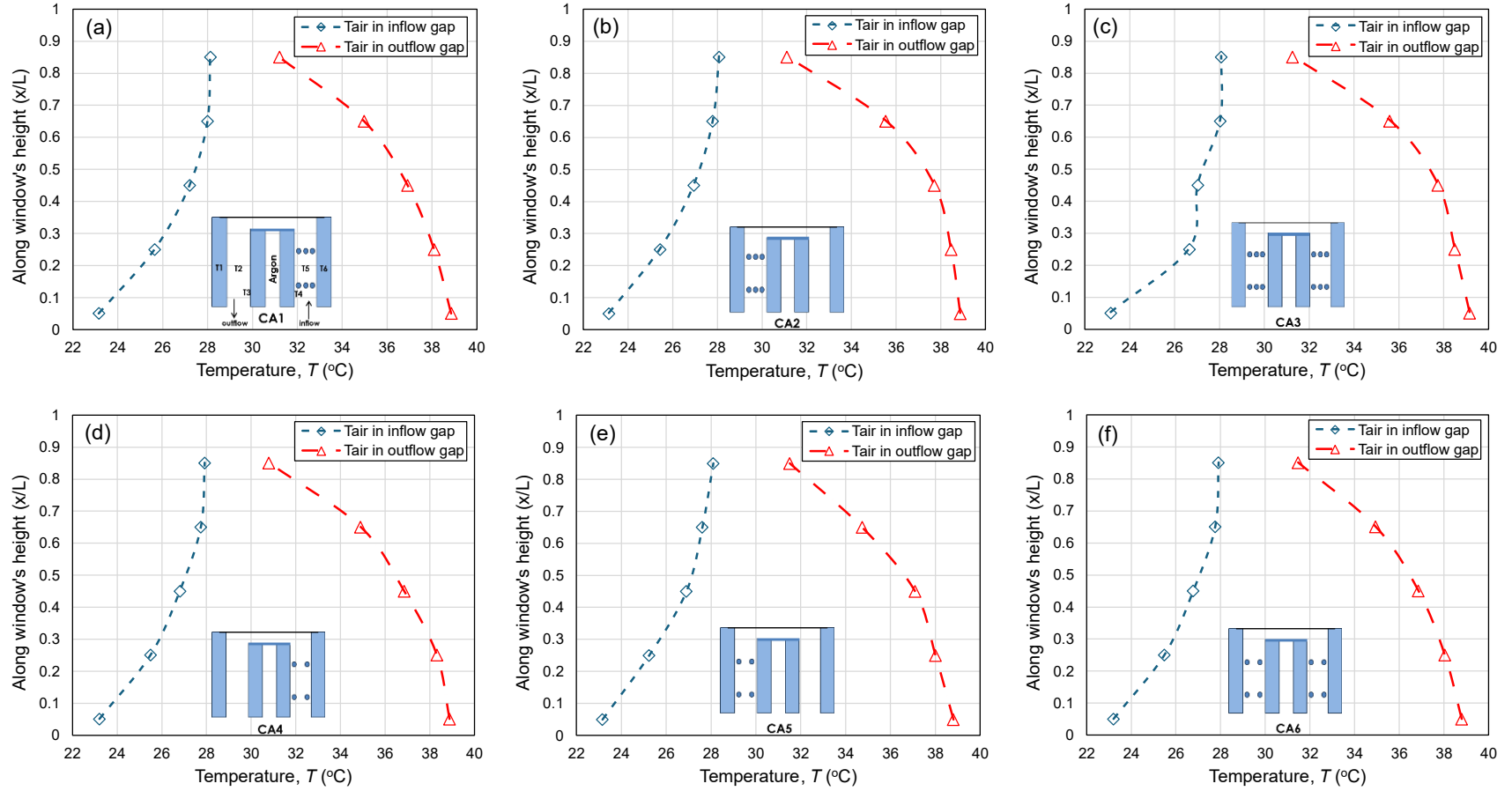


Figure 31. Temperature distribution along the window height (inflow & outflow slots) for a) Alternative 1 (CA₁), b) Alternative 2 (CA₂), c) Alternative 3 (CA₃), d) Alternative 4 (CA₄), e) Alternative 5 (CA₅), f) Alternative 6 (CA₆)

The temperature distribution at the inflow (T_1) and outflow slots (T_2), as indicated in Figure 31, show the thermal efficiency of each alternative. Compared to previous designs, Alternative 2 constantly achieves higher temperatures at the outflow slot (T_2), peaking at 38.87°C at the lower region (P_1). This shows excellent airflow, thermal transmission, and heat absorption. Alternatives 5 and 6 have lower temperatures, indicating less thermal efficiency. These graphical trends show Alternative 2 is best for energy-active windows since it increases heat uptake across the window height.

Analyzing the vertical (height-wise) temperature distribution, each alternative consistently indicates greater heat absorption at the window's lower positions (P_1 – P_2), with decreasing temperatures towards the top (P_4 – P_5), confirming effective convective heat transfer and thermal regulation as air flows upward. Cross-sectional analysis reveals the highest temperatures consistently recorded at external glazing points (T_1), decreasing towards internal surfaces (T_6), confirming effective transfer of thermal energy through intermediate glazing layers (T_3 , T_4) and fluid domains (T_2 , T_5).

4.3.2 Integration of square bars in the EAW system

As shown in Table 21 (Appendix A), the dataset thoroughly illustrates the thermal performance of six square bar configurations integrated into the Energy-Active Window (EAW). Each configuration has been systematically assessed at distinct positions along the window height (P_1 at 0.05 m to P_5 at 0.85 m) and across cross-sectional points (T_1 – T_6). Here, points T_1 and T_6 denote the outermost (exterior) and innermost (interior) glazing panes, respectively, while T_2 and T_5 represent airflow outflow and inflow slots.

As shown in Figure 32, the cross-sectional temperature distribution from the exterior glazing (T_1) inward toward the interior glazing (T_6) displays an efficient, progressive temperature reduction, validating excellent thermal management through intermediate panes and air slots.

Among the evaluated configurations, **Alternative 2** emerges as the most efficient, yielding the highest outflow temperature (39.04°C) and maximum average temperature difference ($\Delta T=16.062^\circ\text{C}$), indicative of superior heat absorption (from the glass pane to the air) and transfer capability. Examining Alternative 2 closely, temperatures at the lowest position (P_1) demonstrate notable heat absorption, with T_1 at 42.41°C and T_2 at 38.94°C , highlighting significant heat transfer to the airflow. As air ascends along the window height toward P_5 , a gradual and consistent decline in temperatures occurs, reaching $T_1=40.41^\circ\text{C}$ and $T_2=31.67^\circ\text{C}$, confirming effective thermal uptake by the airflow before escaping.

Alternatives 1 and 3 also demonstrate commendable thermal performance, closely trailing Alternative 2. Alternative 1 achieves an outflow temperature of 38.77°C and an average ΔT of 15.972°C , while Alternative 3 attains an outflow temperature of 39.00°C with $\Delta T=16.038^\circ\text{C}$. Both alternatives exhibit significant heat absorption at the lower positions (P_1 : $T_1=42.29^\circ\text{C}$ and $T_2=38.85^\circ\text{C}$ for Alternative 1, $T_1=42.39^\circ\text{C}$ and $T_2=39.17^\circ\text{C}$ for Alternative 3) with a diminishing trend upward toward P_5 . Although effective, these alternatives slightly lag Alternative 2, especially in upper positions along the window height and across intermediate panes, implying marginally reduced air-to-glazing heat transfer effectiveness.

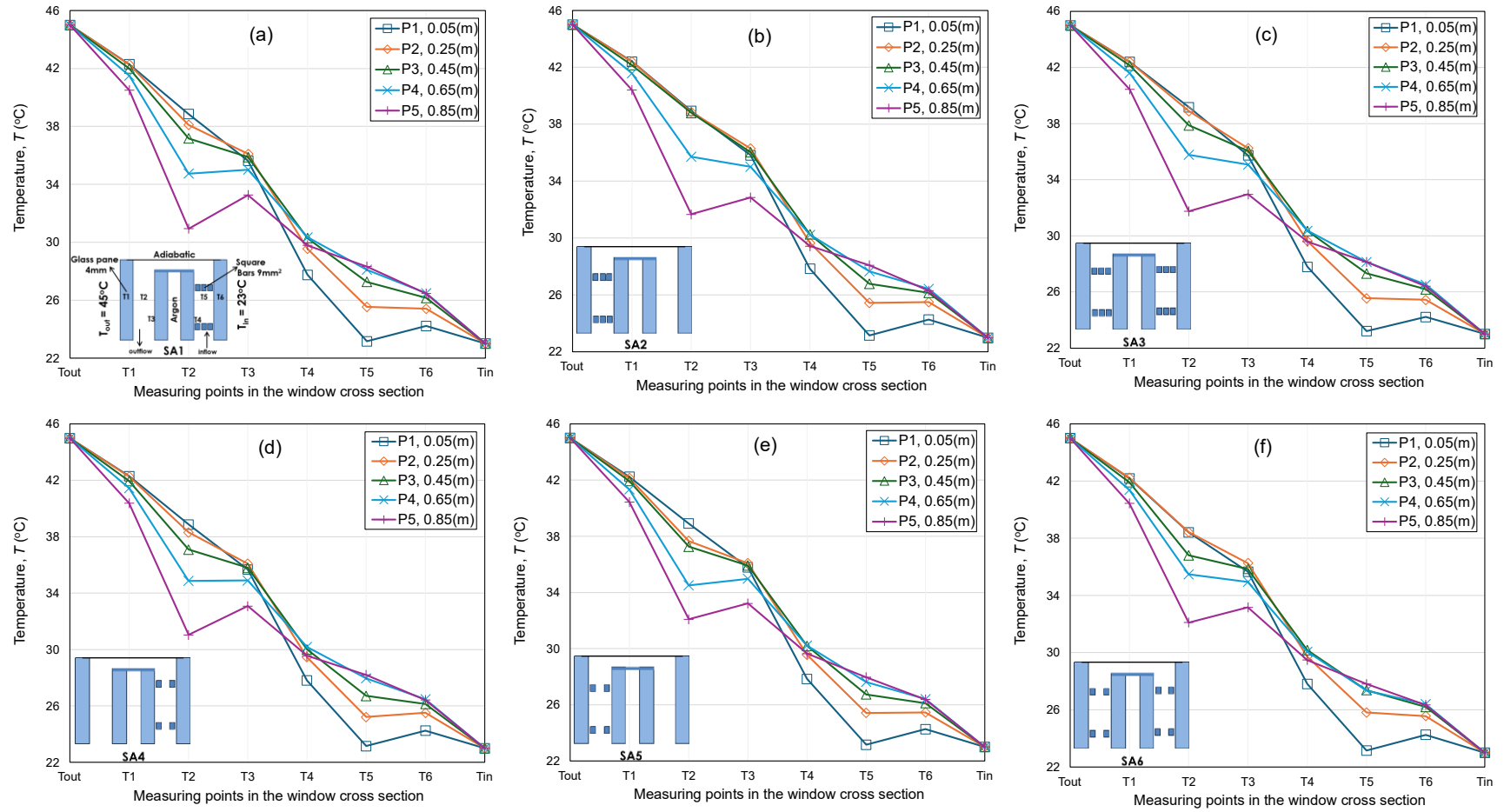


Figure 32. Temperature distribution along the window cross-section for a) Alternative 1 (SA₁), b) Alternative 2 (SA₂), c) Alternative 3 (SA₃), d) Alternative 4 (SA₄), e) Alternative 5 (SA₅), f) Alternative 6 (SA₆)

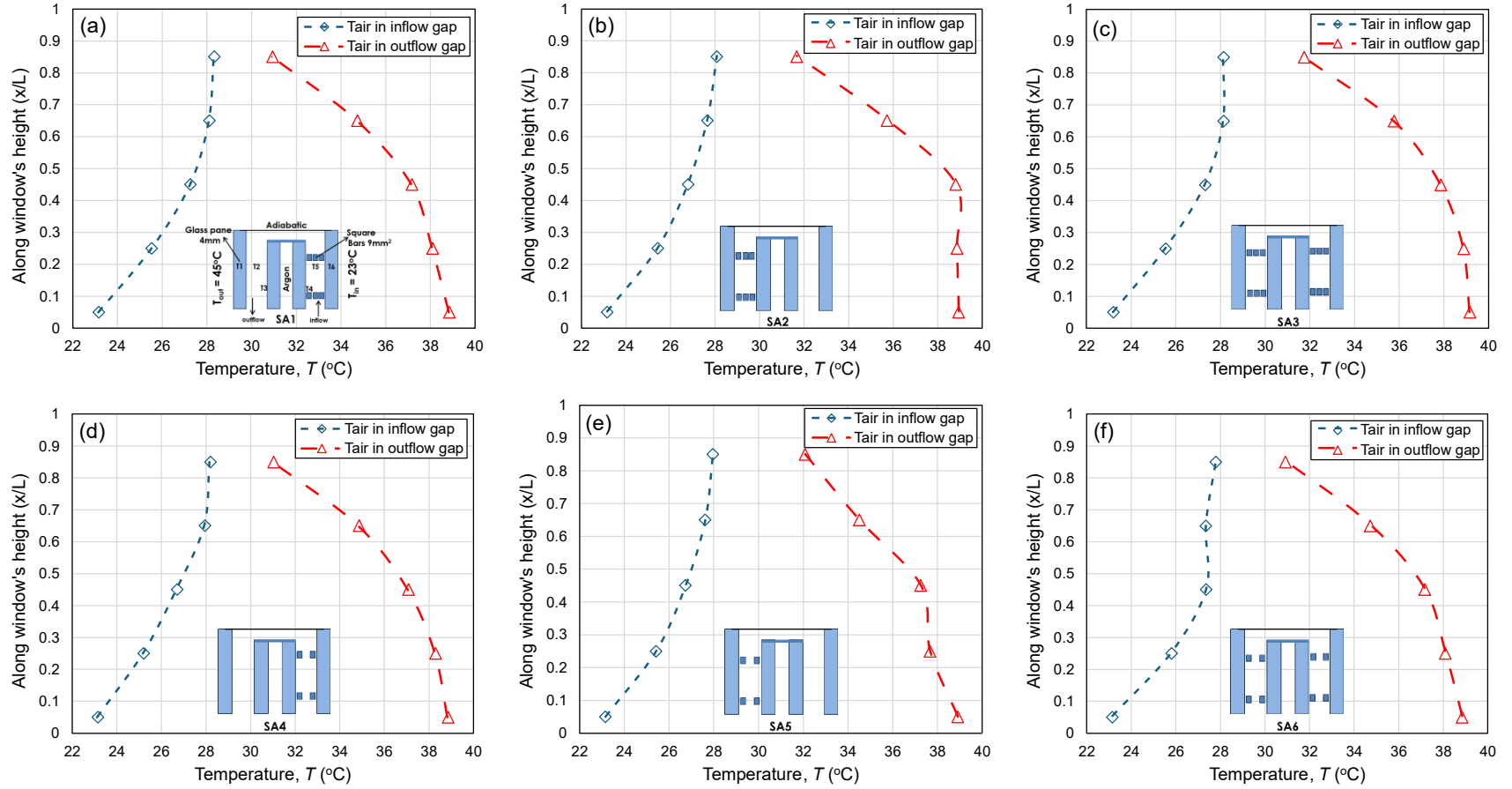


Figure 33. Temperature distribution along the window height (inflow & outflow slots) for a) Alternative 1 (SA₁), b) Alternative 2 (SA₂), c) Alternative 3 (SA₃), d) Alternative 4 (SA₄), e) Alternative 5 (SA₅), f) Alternative 6 (SA₆)

Alternatives 4, 5, and 6 indicate relatively lower efficiency. Alternative 4 presents an outflow temperature of 38.80°C and $\Delta T=15.912^{\circ}\text{C}$, reflecting diminished thermal performance compared to the leading options. Alternative 5 shows the lowest outflow temperature of 38.68°C with $\Delta T=15.892^{\circ}\text{C}$, signaling limited heat transfer efficiency, particularly evident at higher positions along the height (P_5 : $T_2=32.09^{\circ}\text{C}$). Alternative 6 performs slightly better than Alternative 5, with an outflow temperature of 38.81°C and $\Delta T=15.878^{\circ}\text{C}$, yet still falls short relative to the top-performing options, primarily due to reduced convective mixing and heat transfer at upper window positions.

The temperature distribution at the inflow (T_1) and outflow slots (T_2), as illustrated in Figure 33, exhibits the thermal efficiency of each alternative. Compared to earlier designs, Alternative 2 consistently attains elevated temperatures at the outflow slot (T_2), reaching a maximum of 38.94°C in the lower region (P_1). This demonstrates superior airflow, thermal conductivity, and heat absorption. An elevated outflow temperature is particularly important as it directly reflects the system's capacity to transfer more heat from the glazing to the circulating air, enabling potential heat recovery for secondary uses. Alternatives 5 and 6 exhibit reduced temperatures, signifying diminished thermal efficiency, specifically 38.91°C and 38.14°C . The graphical patterns indicate that Alternative 2 is optimal for energy-active windows as it enhances heat absorption (from the glass pane to the air) across the window's height.

Analyzing temperature distribution along the vertical dimension (P_1 to P_5), all square bar alternatives consistently display higher thermal absorption at lower window positions (P_1 – P_2), gradually decreasing towards the top (P_4 – P_5), indicative of a stable convective heat transfer pattern. Across the cross-section, the highest temperatures consistently occur at the

exterior pane (T_1), decreasing toward the interior pane (T_6), demonstrating effective management and transfer of heat through intermediate glazing (T_3 , T_4) and air slots (T_2 , T_5).

4.3.2 Integration of triangular bars in the EAW system

The provided data in Table 22 (Appendix A) and Figure 34 comprehensively evaluate the thermal performance of six triangular bar configurations integrated into the Energy-Active Window (EAW) system at an airflow velocity of 0.24 m/s. Each configuration has been assessed at distinct vertical positions (from P_1 at 0.05 m to P_5 at 0.85 m) and across the cross-sectional points (T_1 – T_6). Specifically, T_1 and T_6 represent the exterior and interior glazing panes, while T_2 and T_5 correspond to the airflow outflow and inflow slots.

Among these alternatives, Alternative 2 exhibits the highest thermal efficiency with an outflow temperature of 38.98°C and the greatest average temperature difference ($\Delta T = 16.028^\circ\text{C}$). At the lower point (P_1), Alternative 2 displays high thermal absorption ($T_1 = 42.38^\circ\text{C}$, $T_2 = 39.12^\circ\text{C}$), indicating excellent heat transfer into the airflow from the exterior glazing. Progressing upward along the height toward the upper point (P_5), the temperature decreases systematically ($T_1 = 40.42^\circ\text{C}$, $T_2 = 31.27^\circ\text{C}$), validating strong convective heat transfer performance as the air moves upward. Cross-sectionally, Alternative 2 shows efficient heat dissipation, with temperatures declining from the external glazing surface (T_1) to the internal pane (T_6), highlighting effective heat distribution and transfer through intermediate panes and air slots.

Alternatives 1 and 3 also demonstrate robust thermal performance, closely following Alternative 2. Alternative 1 achieves an outflow temperature of 38.79°C and $\Delta T =$

15.956°C, and Alternative 3 slightly improves upon this, reaching an outflow temperature of 38.95°C and $\Delta T = 16.014^\circ\text{C}$. Both alternatives exhibit substantial thermal absorption at lower positions (P_1 : Alternative 1, $T_1=42.29^\circ\text{C}$ and $T_2=38.63^\circ\text{C}$; Alternative 3, $T_1=42.37^\circ\text{C}$ and $T_2=39.12^\circ\text{C}$), with temperatures steadily declining upward (toward P_5). However, Alternative 3 slightly outperforms Alternative 1, particularly visible in higher outflow temperature and ΔT , indicating marginally enhanced heat retention.

Alternatives 4, 5, and 6 perform relatively lower. Alternative 4 presents an outflow temperature of 38.82°C and an ΔT_{avg} of 15.95°C, indicating diminished heat absorption capacity compared to Alternatives 1 to 3. Alternative 5, showing the lowest outflow temperature (38.76°C) and a ΔT of 15.944°C, exhibits limited heat transfer efficiency, particularly evident at upper window points (P_5 : $T_2 = 31.38^\circ\text{C}$). Alternative 6, while marginally better than Alternative 5 with an outflow temperature of 38.78°C and ΔT of 15.924°C, still demonstrates reduced performance due to lower overall heat retention, notably at upper vertical and cross-sectional positions. The temperature distribution at the inflow (T_1) and outflow slots (T_2), as illustrated in Figure 35, exhibits the thermal efficiency of each alternative. Compared to earlier designs, Alternative 2 consistently attains elevated temperatures at the outflow slot (T_2), reaching a maximum of 39.12°C in the lower region (P_1). This demonstrates superior airflow, thermal conductivity, and heat absorption. Alternatives 5 and 6 exhibit reduced temperatures, signifying diminished thermal efficiency, specifically 38.82°C and 38.84°C. The visual patterns indicate that Alternative 2 is optimal for energy-active windows as it enhances heat absorption across the height.

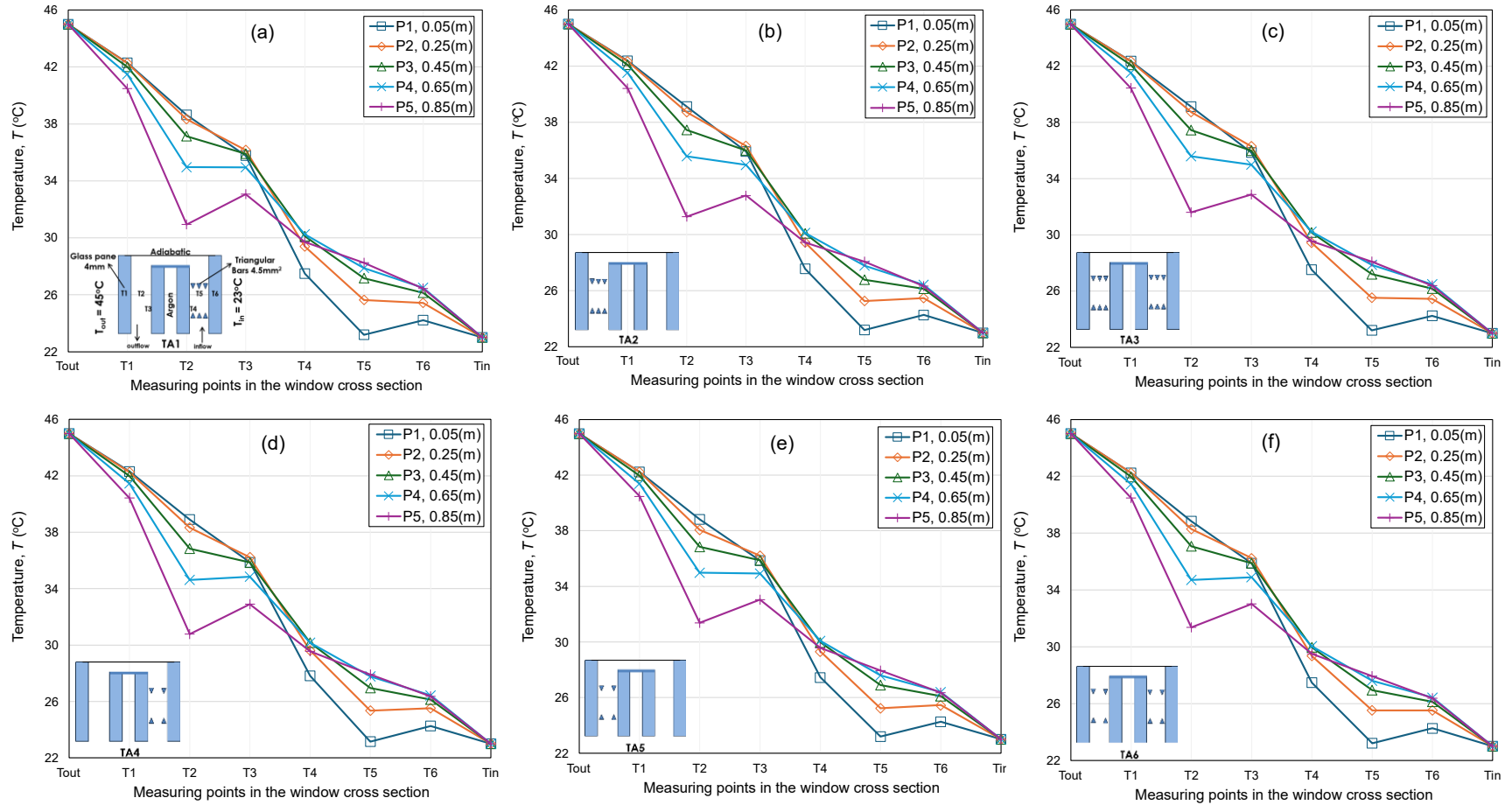


Figure 34. Temperature distribution along the window cross-section for a) Alternative 1 (TA₁), b) Alternative 2 (TA₂), c) Alternative 3 (TA₃), d) Alternative 4 (TA₄), e) Alternative 5 (TA₅), f) Alternative 6 (TA₆)

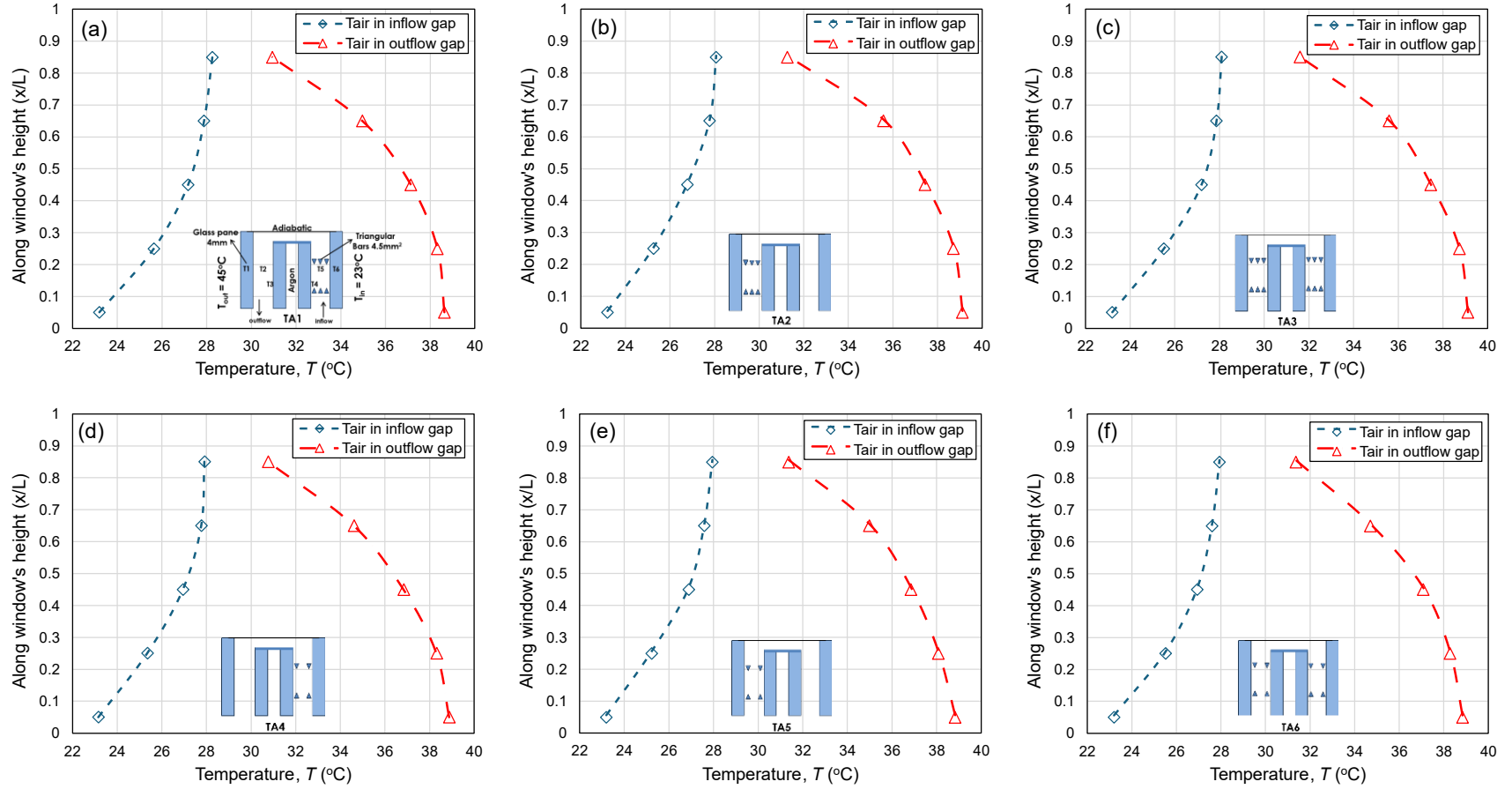


Figure 35. Temperature distribution along the window height (inflow & outflow slots) for a) Alternative 1 (TA₁), b) Alternative 2 (TA₂), c) Alternative 3 (TA₃), d) Alternative 4 (TA₄), e) Alternative 5 (TA₅), f) Alternative 6 (TA₆)

Observing the temperature distribution vertically, all triangular bar configurations consistently reflect higher temperatures at lower positions (P_1, P_2), with gradual reductions toward upper positions (P_4, P_5). This confirms effective convective heat transfer, where the lower air sections absorb more heat, gradually reducing as air moves upward. Cross-sectional analysis consistently shows the highest temperatures at the external glazing (T_1), with a gradual reduction towards internal surfaces (T_6), verifying the controlled and efficient transfer of heat through intermediate glazing layers and air slots.

4.3.3.1 Integration of triangular bars in the EAW system – profile orientation study

The analysis of various triangular bar profile orientations—TA11, TA12, TA13, and TA14—within the Energy-Active Window (EAW) system, as shown in Figure 36, highlights that the four different orientations were examined and how this orientation of airflow elements influences thermal performance.

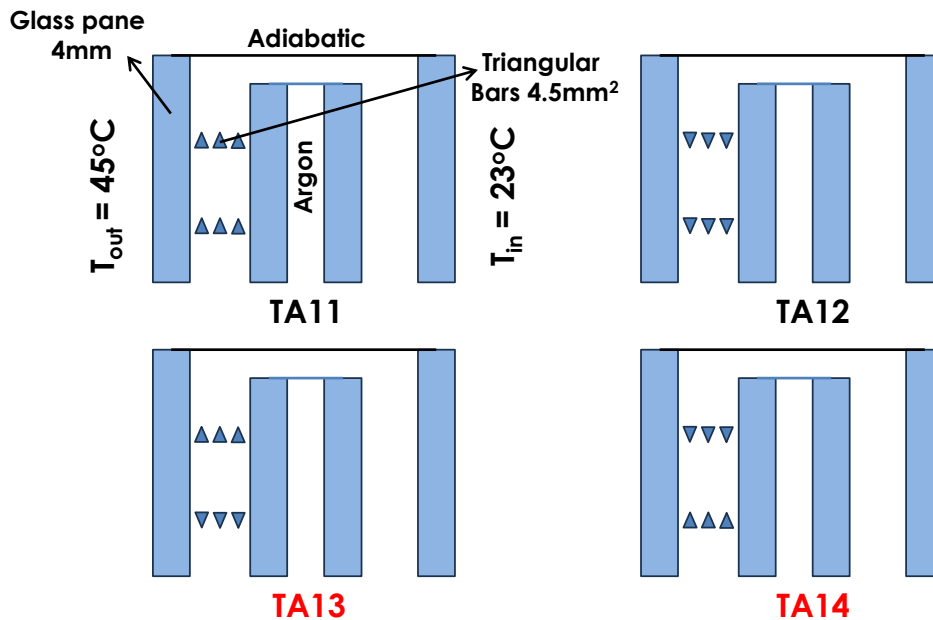


Figure 36. Various orientations for triangular bars in EAW

Among these configurations, orientation TA14 exhibited the highest thermal performance, achieving an outflow temperature of 38.98°C (Alternative 2), as shown in Figure 37. Closely following, orientations TA11 and TA12 showed slightly lower outflow temperatures of 38.96°C and 38.97°C, respectively, indicating marginally reduced heat absorption effectiveness compared to TA14. Interestingly, orientation TA13 yielded identical thermal performance to TA14, emphasising that certain symmetrical placements or similar airflow characteristics result in comparable thermal behaviour. Thus, the results underline that bar orientation can have subtle yet meaningful impacts on airflow dynamics and heat transfer efficiency. As seen with TA14 (and similarly TA13), selecting an optimal bar orientation ensures maximum convective heat uptake and thermal management within the EAW system, improving overall thermal performance.

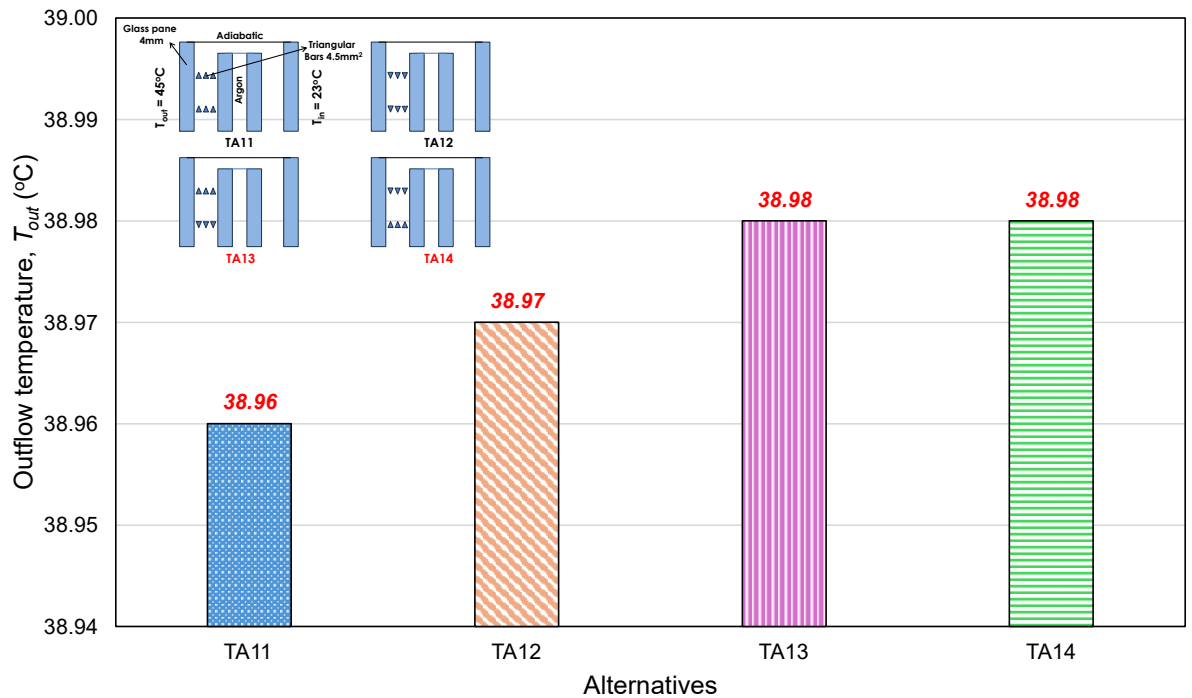


Figure 37. Outflow temperature for various triangular bar orientations in EAW system

4.4 Best alternative based on calculated outflow and inflow-outflow

temperature difference

The provided Table 23 (Appendix A) illustrates a detailed comparison of various airflow element configurations—circular, square, and triangular bars—integrated within the EAW system, each assessed against the base case scenario as shown in Figure 38 (a). Evaluating thermal performance based on return air (outflow) temperatures indicates that certain configurations significantly enhance heat uptake from the external glazing compared to the base case (38.8°C).

In the circular bar configuration, alternative CA2 (three bars positioned at 0.1 m intervals in the outflow air slot only) achieves the highest return air temperature (39.00°C) and maximum ΔT (16.00°C). This improvement is attributed to the optimized placement of bars enhancing turbulent mixing and increasing convective heat transfer by effectively disrupting airflow and reducing boundary layer formation. In contrast, alternatives with fewer bars (CA4, CA5, and CA6) or placement solely in inflow slots exhibited lower return air temperatures (38.76°C–38.82°C), primarily because the configurations facilitated increased airflow velocities, resulting in reduced air residence time and diminished heat absorption from glazing surfaces.

Square bar alternatives show a similar trend, with alternative SA2 (three bars at 0.1 m intervals in the outflow slot only) delivering the best thermal performance, achieving an outflow temperature of 39.04°C and ΔT of 16.04°C. This clearly surpasses the base case scenario, emphasizing the role of square bars in enhancing heat transfer by inducing

turbulence and extending residence time. Alternatives with reduced numbers of bars or inflow-only arrangements, such as SA4 and SA5 (38.80°C and 38.68°C), demonstrated lower effectiveness due to accelerated airflow velocity and subsequently lower heat retention capability.

The triangular bar configurations further confirm this behavior, with TA2 (three bars in the outflow slot) and orientation-specific alternatives TA13 and TA14 achieving superior thermal performance (return air temperature 38.98°C and $\Delta T=15.98^{\circ}\text{C}$). The triangular profile facilitated a pronounced airflow disruption in these arrangements, promoting better mixing and heat absorption. Conversely, configurations with fewer bars or suboptimal placements (TA4, TA5, and TA6) presented reduced performance (38.76°C–38.82°C), illustrating how less effective arrangements accelerate airflow, diminishing the residence time and heat transfer. Where $\Delta T_{\text{of-if}}$ (outflow – inflow) temperature for each alternative, as shown in Figure 38 (b).

These results underline a consistent trend: airflow element configuration, profile, quantity, and positioning profoundly influence airflow dynamics within the EAW system. Optimal configurations, particularly in the outflow slot, prolong air residence time, enhance turbulence, and facilitate more effective convective heat transfer, significantly improving the thermal performance compared to the baseline scenario. Conversely, less effective configurations inadvertently accelerate airflow, reducing the opportunity for heat exchange and consequently diminishing system effectiveness.

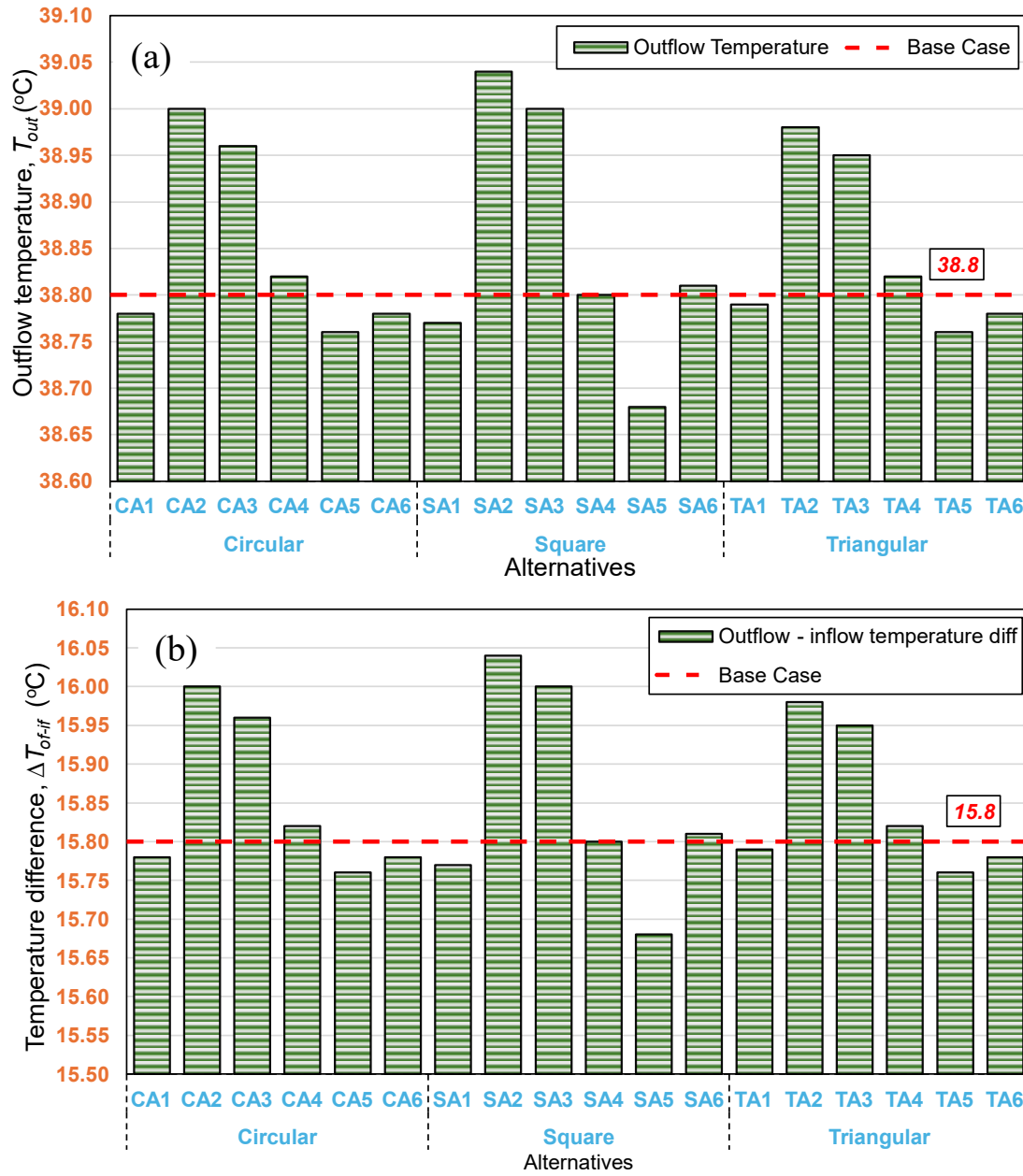


Figure 38. Comparison of a) Outflow temperature & b) Outflow–inflow temperature difference for various EAW alternatives with EAWo

4.5 Comparison of average pane temperature differences: EAW_b vs.

EAW_o and conventional glazing

The average pane temperature difference calculated from Equation (19) offers valuable insights into the thermal performance of various glazing configurations under extreme temperature conditions (outdoor: 45°C; indoor: 23°C). Among the options, the Square Bar Alternative 2 (SA2) demonstrated the highest temperature differential of 16.06°C, as shown in Figure 39, indicating the most effective resistance to heat transfer from outside to inside. This suggests superior insulation performance and highlights SA2 as the best-performing configuration for minimizing heat gain.

Closely following SA2 are the Circular (CA2) and Triangular (TA2) configurations, with temperature differences of 16.04°C and 16.03°C, respectively, both outperforming the base energy-active window (EAW) case, which recorded 15.90°C. In contrast, conventional triple-glazed and double-glazed windows showed significantly lower temperature differentials of 13.14°C and 9.37°C, respectively, indicating higher heat transfer and, thus, lower thermal performance. The comparison emphasizes the enhanced insulating capability of the optimized energy-active window configurations, particularly SA2, in reducing indoor heat gain in hot climate conditions.

$$\Delta T_{avg} = \frac{(P_1^{og} - P_1^{ig}) + (P_2^{og} - P_2^{ig}) + (P_3^{og} - P_3^{ig}) + (P_4^{og} - P_4^{ig}) + (P_5^{og} - P_5^{ig})}{5} \quad (19)$$

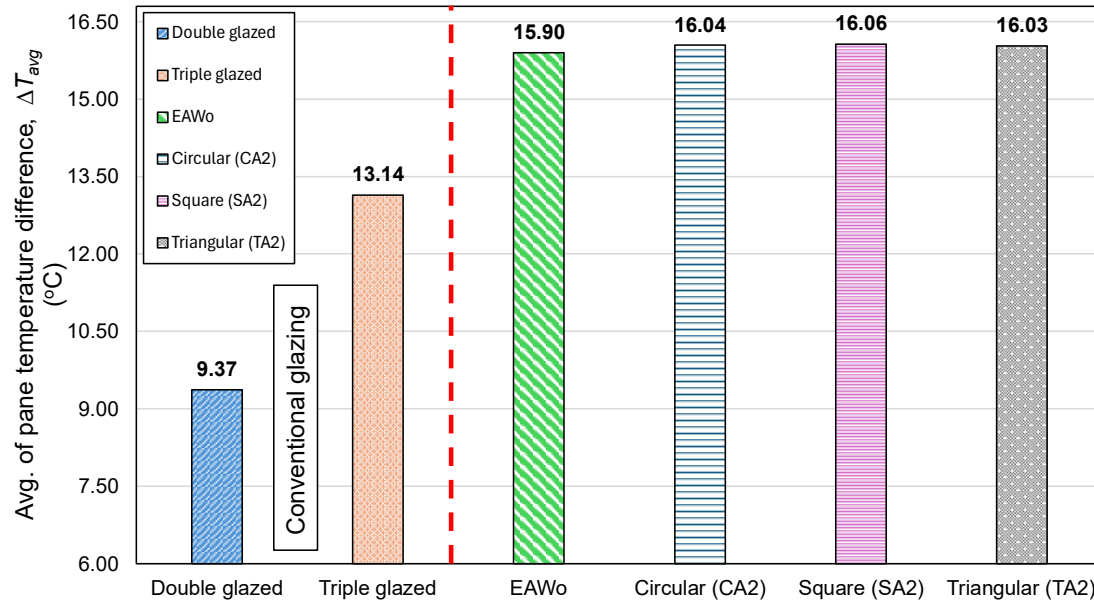


Figure 39. The average value of the pane temperature difference between conventional glazing and EAW systems

4.6 EAW system with square bars, EAW_b – Alternative 2 (SA2)

As presented in Figure 40 is the comparative analysis of outflow temperature (pressure outlet) between the EAWo and the best-performing alternative—square bars (SA2) configuration—at varying velocities ranging from 0.24 to 0.57 m/s. The results clearly demonstrate that the square bar configuration consistently achieves higher outlet temperatures across all tested velocities. Specifically, at the lowest velocity (0.24 m/s), the square bar configuration achieves an outflow temperature of 39.04°C compared to 38.81°C in the base case. This trend persists at increasing velocities, with SA2 maintaining consistently elevated temperatures—38.31°C at 0.33 m/s, 37.62°C at 0.41 m/s, and 36.94°C at 0.49 m/s, compared to corresponding base case temperatures of 37.87°C, 36.98°C, and 36.14°C, respectively. Even at the highest tested velocity (0.57 m/s), the

square bar arrangement still outperforms the base case, showing a temperature of 36.45°C versus 35.36°C.

These findings highlight the effectiveness of square bars in enhancing convective heat transfer within the Energy-Active Window system. The improved thermal performance can be attributed to the increased turbulence and disrupted airflow patterns created by the square bars, resulting in greater heat absorption and retention. This underscores the significance of geometric optimization and strategic placement of airflow elements, which can substantially boost the thermal efficiency of EAW systems, especially at lower velocities due to increased air residence time.

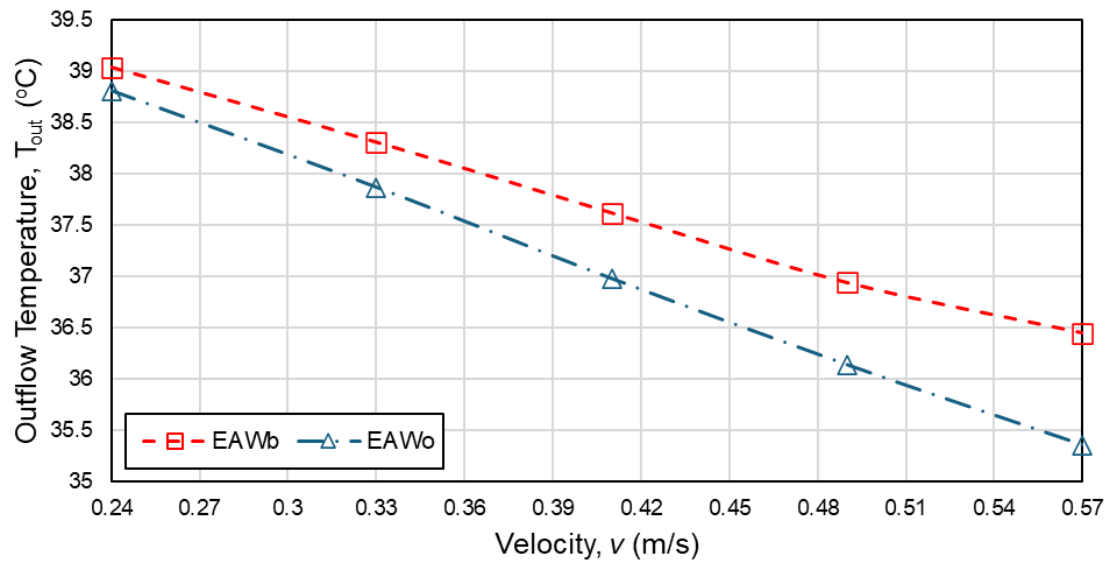


Figure 40. Comparison of EAW_b with EAW_o based on outflow temperature

Moreover, Figure 41 illustrates the average pane temperature difference (ΔT) between the external (T_1) and internal (T_6) glazing surfaces of the Energy-Active Window (EAW)

system, considering the base case and the optimal square-bar configuration (Alternative 2, SA2) across different airflow velocities.

The table shows that the integration of square bars consistently results in a higher temperature difference than the base case, indicating improved thermal efficiency. At the lowest velocity of 0.24 m/s, the square-bar configuration shows a temperature difference of 16.06°C, marginally higher than the base case (15.97°C). This trend remains consistent as velocity increases; at 0.33 m/s, the square bars achieve a temperature difference of 16.04°C compared to 15.96°C in the base case. Even at higher velocities (0.41, 0.49, and 0.57 m/s), the square bar arrangement maintains a higher ΔT (15.99°C, 15.95°C, and 15.91°C) compared to the base case values (15.90°C, 15.82°C, and 15.73°C, respectively).

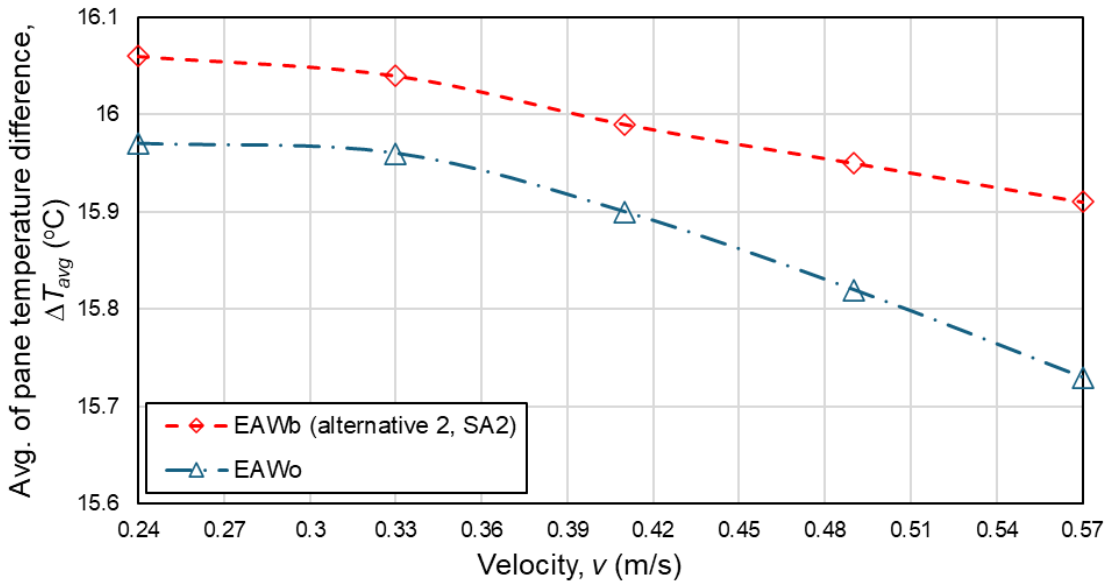


Figure 41. Average value of the pane temperature difference between EAW_b and the EAW_o

These results clearly illustrate the effectiveness of square bars in enhancing heat absorption and maintaining a higher temperature gradient between the external and internal glazing

surfaces. The geometric disturbance created by the square bars enhances turbulence and mixing, effectively increasing the thermal energy exchange and heat retention within the airflow. This improved thermal gradient ultimately contributes positively to the EAW system's overall thermal performance and efficiency.

4.7 Thermal performance of EAW_b system at various velocities

The thermal performance analysis from Table 24 (Appendix A) presents the best-case square bar configuration (Alternative 2, SA2). It demonstrates superior heat transfer capabilities compared to the base case, especially at lower velocities (0.24 m/s and 0.33 m/s). At the lowest velocity (0.24 m/s), the system reaches the highest return air temperature (RAT) of 39.04°C with an average pane temperature difference (ΔT) of 16.062°C, attributed primarily to prolonged air residence time allowing optimal heat absorption (T_2 at the outflow slot reaches 38.94°C at P_1) shown earlier in Figure 34. As airflow velocity increases (0.33 m/s to 0.57 m/s), outflow temperature and ΔT_{avg} gradually decline to 36.45°C and 15.912°C, respectively, highlighting reduced thermal effectiveness due to decreased residence time. The shorter air retention at higher velocities restricts sufficient heat uptake, lowering temperature distribution across the height (e.g., T_2 at P_5 drops significantly from 31.67°C at 0.24 m/s to 30.27°C at 0.57 m/s) as shown in Figure 42.

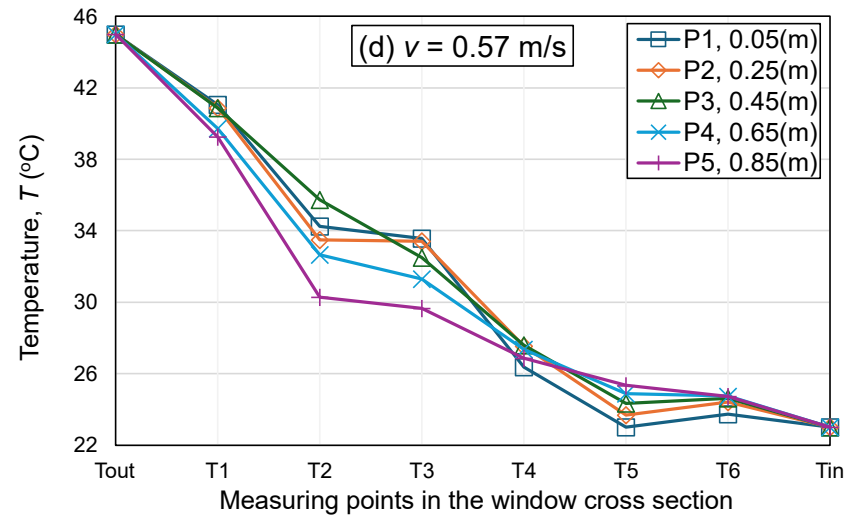
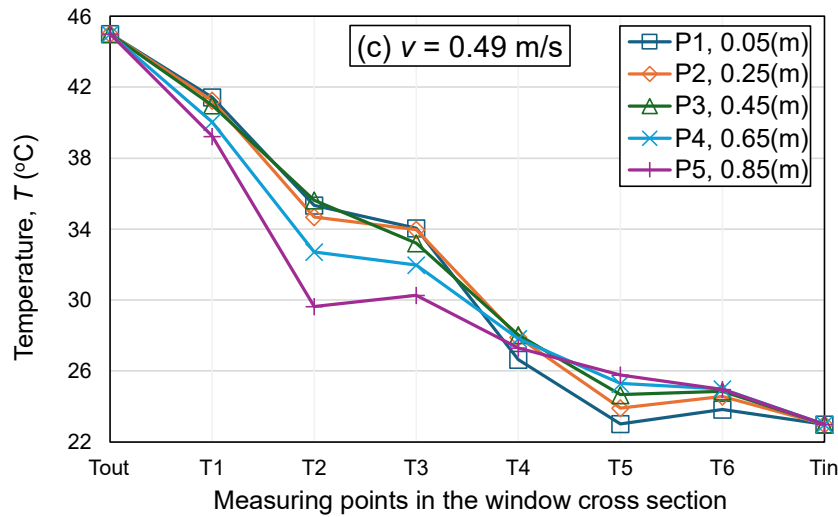
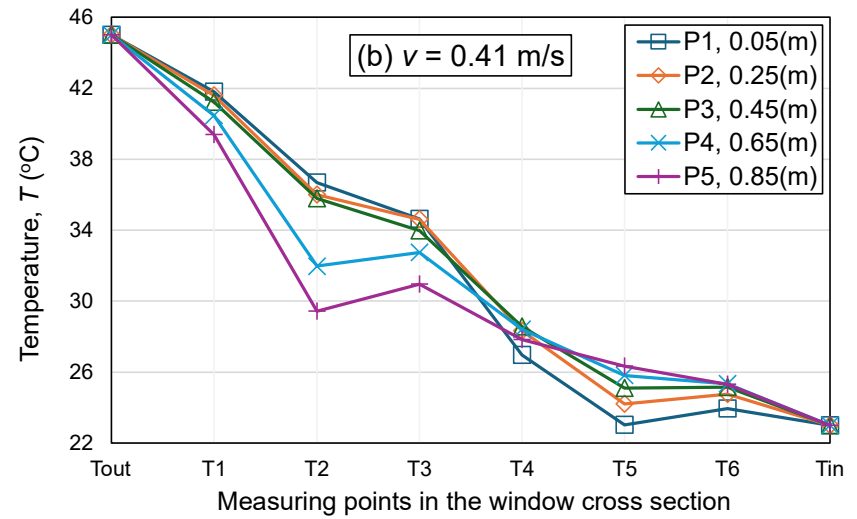
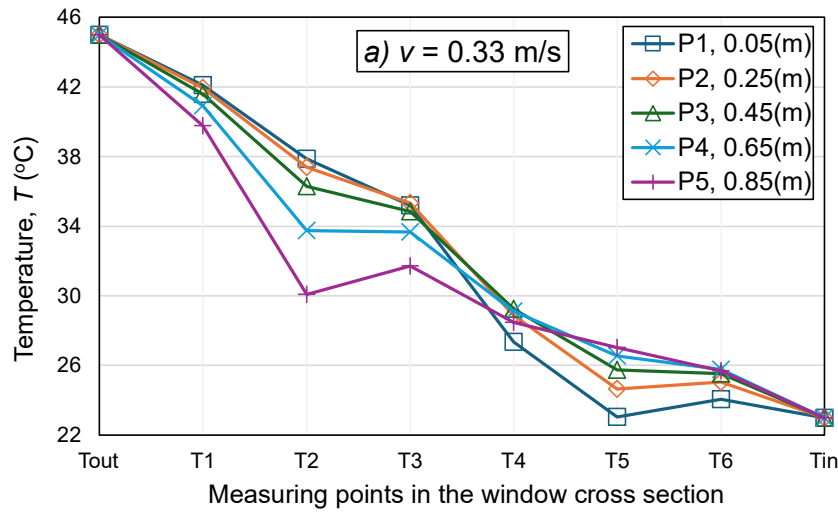


Figure 42. a) Thermal performance of EAW_b at velocity: a) 0.33 m/s, b) 0.41 m/s, c) 0.49 m/s, d) 0.57 m/s along the cross-section

Cross-sectional temperature distributions remain consistently favorable across all velocities, displaying effective heat transfer from the external pane (T_1) through intermediate panes (T_3 and T_4) to the internal pane (T_6). However, faster airflow at higher velocities noticeably reduces overall thermal efficiency despite the optimized square bar geometry, underscoring the importance of selecting an airflow velocity that balances heat absorption efficiency with airflow requirements. This optimal balance is achieved particularly at lower velocities, demonstrating enhanced overall performance relative to the EAW base case.

4.8 Thermal performance of EAW system: Square bar configuration

best case (SA2) at various outdoor and inflow temperatures

The thermal performance of the best-case square bar configuration (Alternative 2, $v = 0.24$ m/s), as shown in Table 25 (Appendix A), was thoroughly evaluated at various outdoor (41°C , 43°C , 45°C) and supply air temperatures (inflow temperature = 19°C , 23°C , 25°C). It was observed that increasing outdoor temperatures consistently resulted in elevated return outflow temperature, indicative of enhanced heat transfer and thermal energy absorption. For instance, with a fixed inflow temperature of 23°C , the outflow temperature rose from 36.12°C at an outdoor temperature of 41°C to 37.58°C at 43°C , demonstrating more effective heat uptake. Similar trends were found at higher inflow temperatures of 25°C , where outflow temperature improved significantly from 36.65°C at 41°C outdoors to 39.57°C at 45°C , highlighting the system's efficient thermal performance as both inflow temperature and external temperatures increased, as shown in Figure 43.

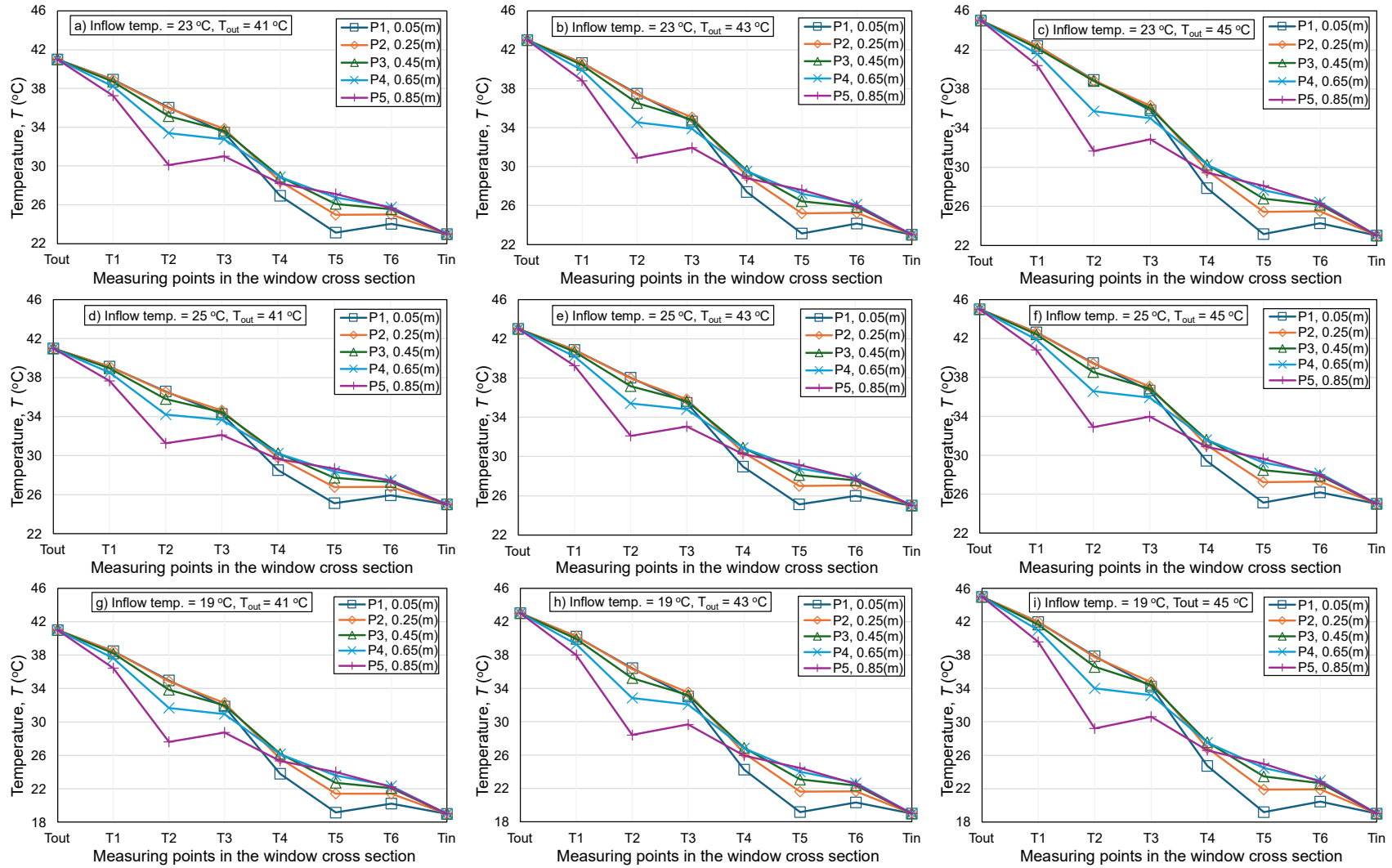


Figure 43. Thermal performance of EAWs at various outdoor and inflow temperatures

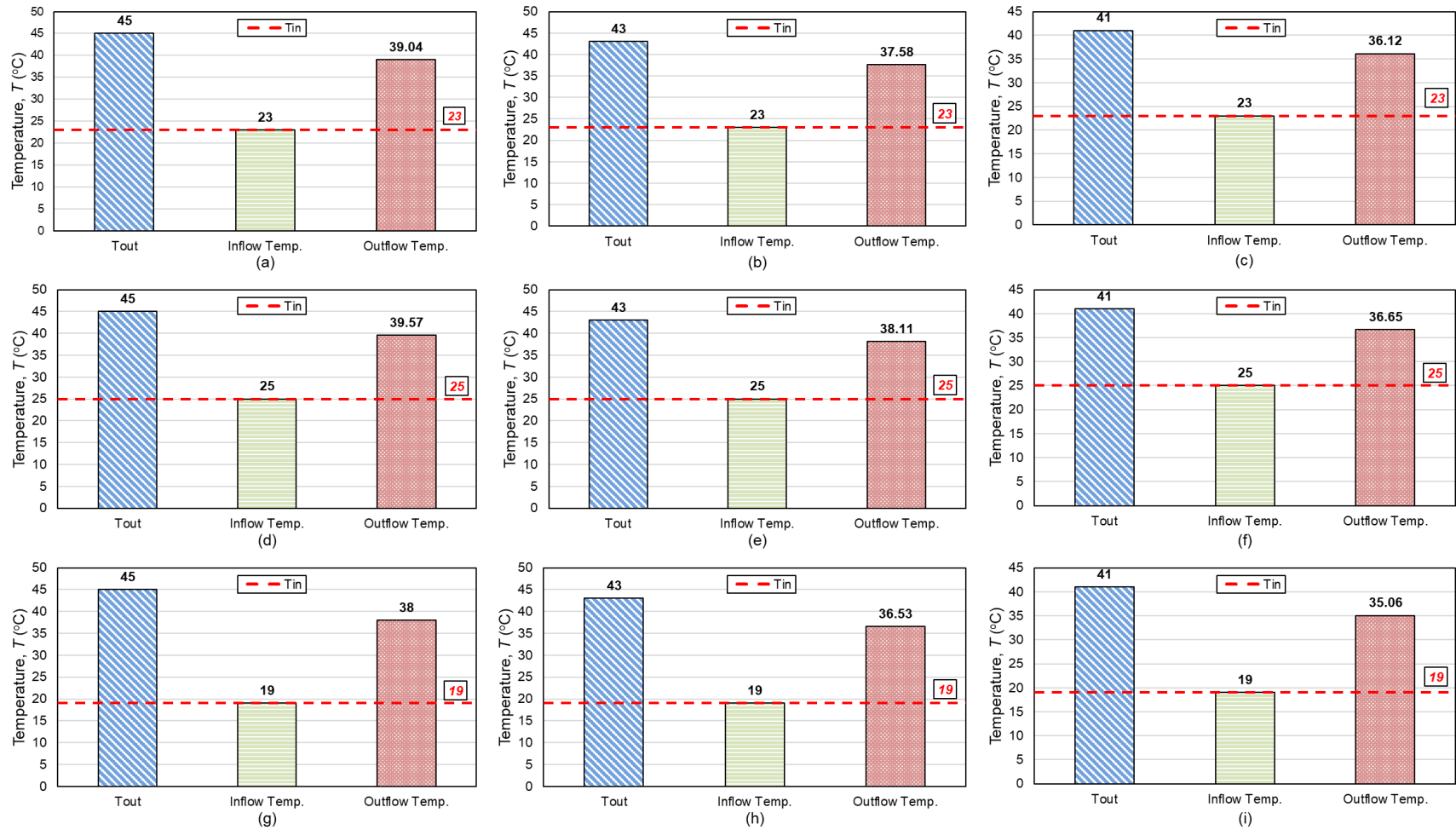


Figure 44. EAW_b at various inflow and outdoor temperatures

Conversely, reducing the supply air temperature to 19°C notably increased the overall pane temperature difference (ΔT), achieving maximum values such as 21.51°C at 45°C outdoor temperature, illustrating superior heat absorption due to higher temperature gradients between panes and airflow, as shown in Figure 44. However, the outflow temperature values at this lower inflow temperature were comparatively modest, peaking at 38°C (45°C outdoor). This suggests that although lower inflow temperature enhances temperature gradients, the actual air temperature leaving the system is moderately impacted due to significant heat absorption occurring near inlet regions (T_5 and T_6). The best-case square bar configuration performed consistently well across varying temperatures, confirming its effectiveness in maintaining favorable indoor conditions under diverse climatic scenarios.

4.9 Study on bar spacing for EAW best case (with square bars

alternative 2- SA2) optimization

To further optimize the thermal performance of the Energy-Active Window (EAW) system, a detailed investigation was conducted on the effect of bar spacing within the best-performing square bar configuration (SA2), as shown in Figure 45.

Three spacing configurations, 0.1 m, 0.2 m, and 0.05 m centre-to-centre (c/c), were evaluated, as shown in Table 18, to understand how the density of the square bars in the airflow path influences heat transfer. This parametric study aims to determine the most effective arrangement that balances airflow resistance and thermal interaction, ultimately enhancing return air temperature and energy efficiency.

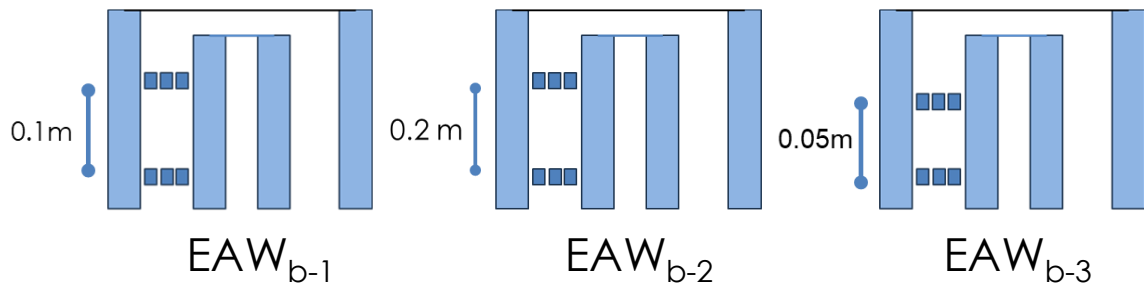


Figure 45. EAW_b optimization with: a) 0.1m spacing c/c, b) 0.2m spacing, c) 0.05m spacing c/c

Table 18. EAW_b variants based on bar spacing

Cases	Description
EAW square bars- best case-1	(bars at 0.1m c/c)
EAW square bars- best case-2	(bars at 0.2m c/c)
EAW square bars- best case-3	(bars at 0.05m c/c)

The presented Figure 46 results highlight the influence of bar spacing on the thermal behavior of the EAW system's best case (SA2) with optimized bar setup, particularly regarding the inner glazing temperature and the temperature difference between the outflow and inflow air (ΔT). Compared to the base case ($\Delta T = 15.8^\circ\text{C}$ and inner glazing temperature = 25.73°C), all three variations of the best square bar configurations demonstrate improved thermal performance, with best case-3 (bars at 0.05 m c/c) standing out significantly. This configuration achieves the highest ΔT of 16.45°C , indicating superior heat absorption of 0.65°C from the base case, glazing layers and more effective convective transfer to the airflow. Interestingly, this case also shows a notable drop in inner glazing temperature to 23.3°C , reducing 2.45°C from the base case. This suggests that the

denser bar arrangement enhanced thermal interaction and carried away more heat from the glazing surface, thereby decreasing its retained temperature.

In contrast, best case-1 (0.1 m c/c) and best case-2 (0.2 m c/c) offer moderate improvements in ΔT (16.04°C and 15.96°C, respectively), with inner glazing temperatures closely aligned with the base case. The subtle difference between them suggests that although slightly wider bar spacing maintains air mixing, it does not exploit the full potential of convective heat capture. On the other hand, case 3's tighter bar arrangement enhances the contact area and residence time, promoting more intense thermal exchange. So, reducing the spacing between square bars significantly improves the heat extraction capacity of the EAW system while also effectively cooling the inner glazing surface, making the best case-3 the most thermally efficient configuration.

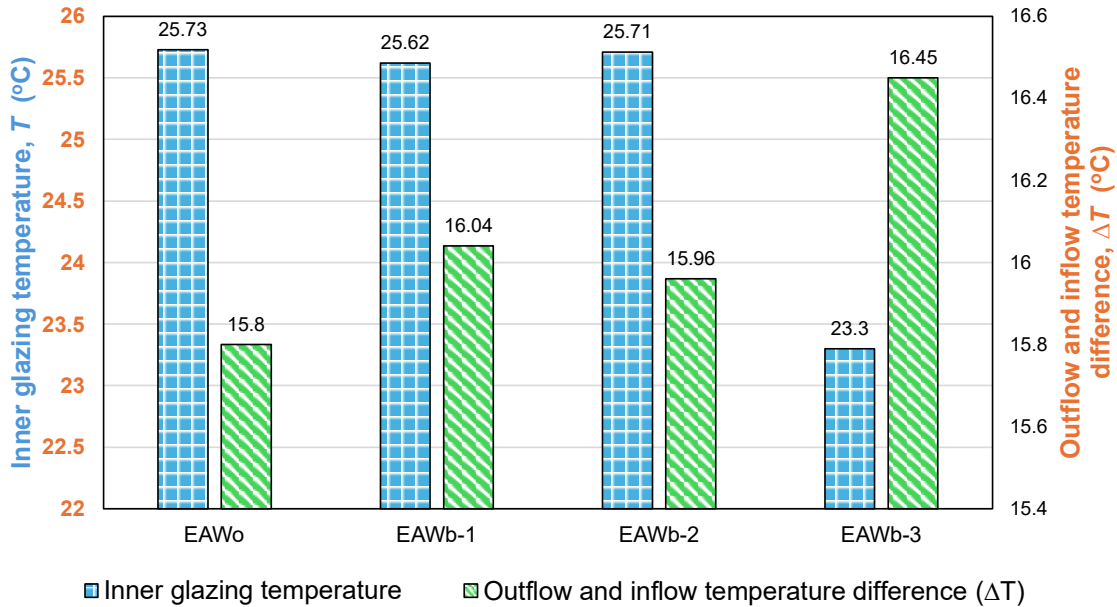


Figure 46. Comparison of the EAWo with optimized EAW_{b-3} (with square bar variants)

4.10 U-values for EAW systems vs. conventional glazing

The U-value comparison, shown in Figure 47, clearly highlights the superior thermal insulation performance of the Energy-Active Window (EAW) in its optimized configuration. The U-value is calculated using the energy balance equation, and it is related to the temperature gradient between the indoor air, the inner glazing surface, and the outdoor environment. A lower U-value indicates better insulation capacity, meaning less heat transfer through the window structure.

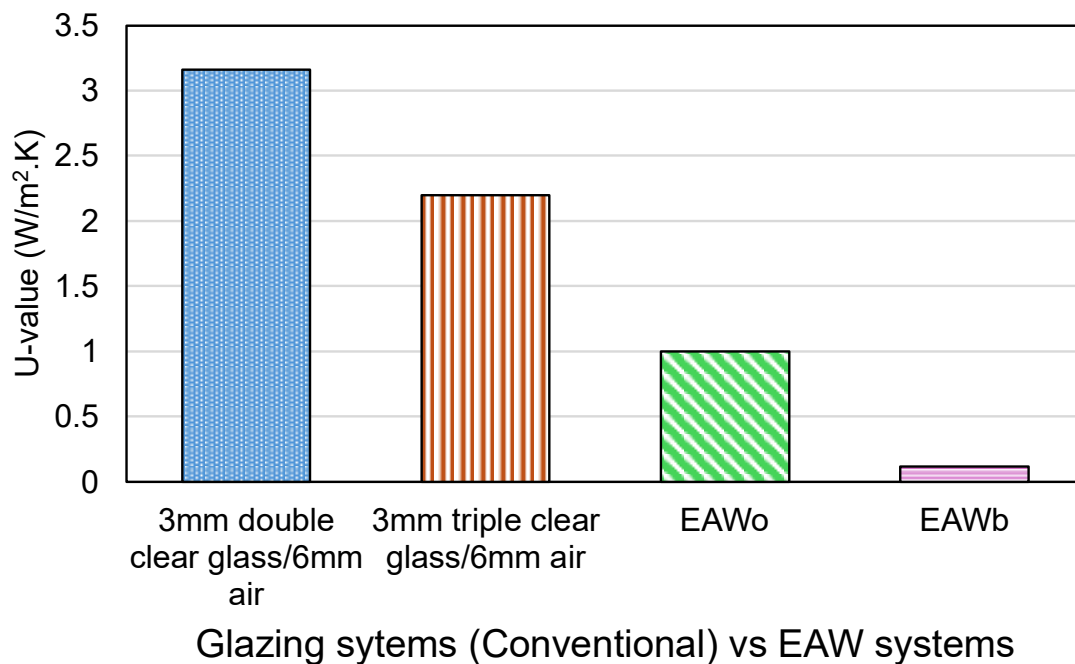


Figure 47. U-values for EAW systems and conventional glazing systems

From the results, the EAWo shows a U-value of 1, which already performs better than conventional glazing materials such as single clear glass ($5.8 \text{ W/m}^2\cdot\text{K}$), double clear glass with 6 mm air gap ($3.16 \text{ W/m}^2\cdot\text{K}$), and triple clear glass with a 6 mm air gap ($2.2 \text{ W/m}^2\cdot\text{K}$). However, the best-performing EAW configuration—with square bars spaced at 0.05 m

centre-to-centre (best case-3) demonstrates a significantly reduced U-value of **0.12**, representing an 88% improvement over the base case.

This drastic drop in the U-value for the optimized EAW system indicates a substantial reduction in conductive heat transfer, owing to enhanced convective interaction, better thermal buffering due to airflow design, and more effective surface cooling of the inner glazing. Not only does this improve indoor comfort by maintaining lower inner surface temperatures, but it also contributes meaningfully to energy conservation, making the EAW best case far superior to both traditional and base case window systems in terms of thermal insulation and sustainable energy performance.

4.11 Heat and flow field distribution across EAW configurations

Figures 49 (a and b) in the provided images represent the velocity and temperature contours for various Energy-Active Window (EAW) alternatives integrating triangular bar geometries. These contour plots offer valuable insights into the thermal and flow behavior within the cavity region, directly reflecting the influence of geometry on air circulation and heat transfer.

4.11.1 Velocity contours

The velocity contours reveal significant variations in airflow distribution patterns caused by different bar configurations. Notably, the highest velocity magnitudes evident in red are concentrated ($\sim 1.20 - 1.34$ m/s) around the inlet slots and the immediate downstream region of the triangular bars. Triangular bars, due to their angled surfaces, generate symmetric vortices and well-defined recirculation zones, enhancing internal mixing and

residence time. In contrast, circular bars yield smoother but less disruptive flow, while square bars intensify directional redirection. Poorly optimized shapes or sparse arrangements lead to accelerated exit flow and reduced contact time with glazing surfaces. Thus, bar geometry critically controls velocity distribution, affecting convective heat transfer potential.

4.11.2 Temperature contours

In Figure 48 (b), static temperature contours reveal distinct thermal gradients across the EAW cavity, ranging from approximately 45.0 – 42.6 °C near the outer glazing to 23.0 – 25.0 °C near the inner pane. This indicates effective thermal absorption through the glazing layers. Particularly in the middle and upper zones, where air diverts toward the outflow slots, the temperature gradients intensify, with values near these redirection zones reaching around 37.0–40.0 °C, highlighting regions of significant heat uptake before the air exits. The effect of configuration shape is evident: triangular bars generate smoother and more extended isotherms, facilitating deeper thermal penetration and slower cooling within the cavity. In contrast, less streamlined or sparsely arranged shapes result in sharper temperature drops, e.g., from ~41.0 °C to ~28.0 °C over short spans, reflecting faster transitions and limited heat retention. These observations confirm that optimized geometry enhances thermal diffusion and storage, whereas suboptimal setups lead to insufficient air–surface interaction and lower thermal exchange efficiency.

4.12 Solution residuals

Figures 49 (a) and (b) represent the convergence behavior of the CFD simulation conducted for evaluating the thermal and fluid flow performance of the Energy Active Window (EAW) system. Figure 49 (a) illustrates the temperature convergence at multiple measurement points (from P1-T1 to P1-T6) strategically placed across the window cross-section. After approximately 250 iterations, temperatures stabilize, indicating successful thermal equilibrium within the simulated system and validating the stability of the numerical solution.

Figure 49 (b) presents the convergence residuals of key CFD parameter continuity, x-velocity, y-velocity, and energy equations. It shows a steady and continuous decrease in residual values for all parameters, with energy residuals achieving convergence at an order of magnitude below 10^{-14} , continuity reaching below 10^{-6} , and velocity components below 10^{-10} , perfectly aligning with the previous study [73]. Such minimal residual values demonstrate robust convergence and ensure the reliability and accuracy of the simulation results obtained for the EAW performance analysis.

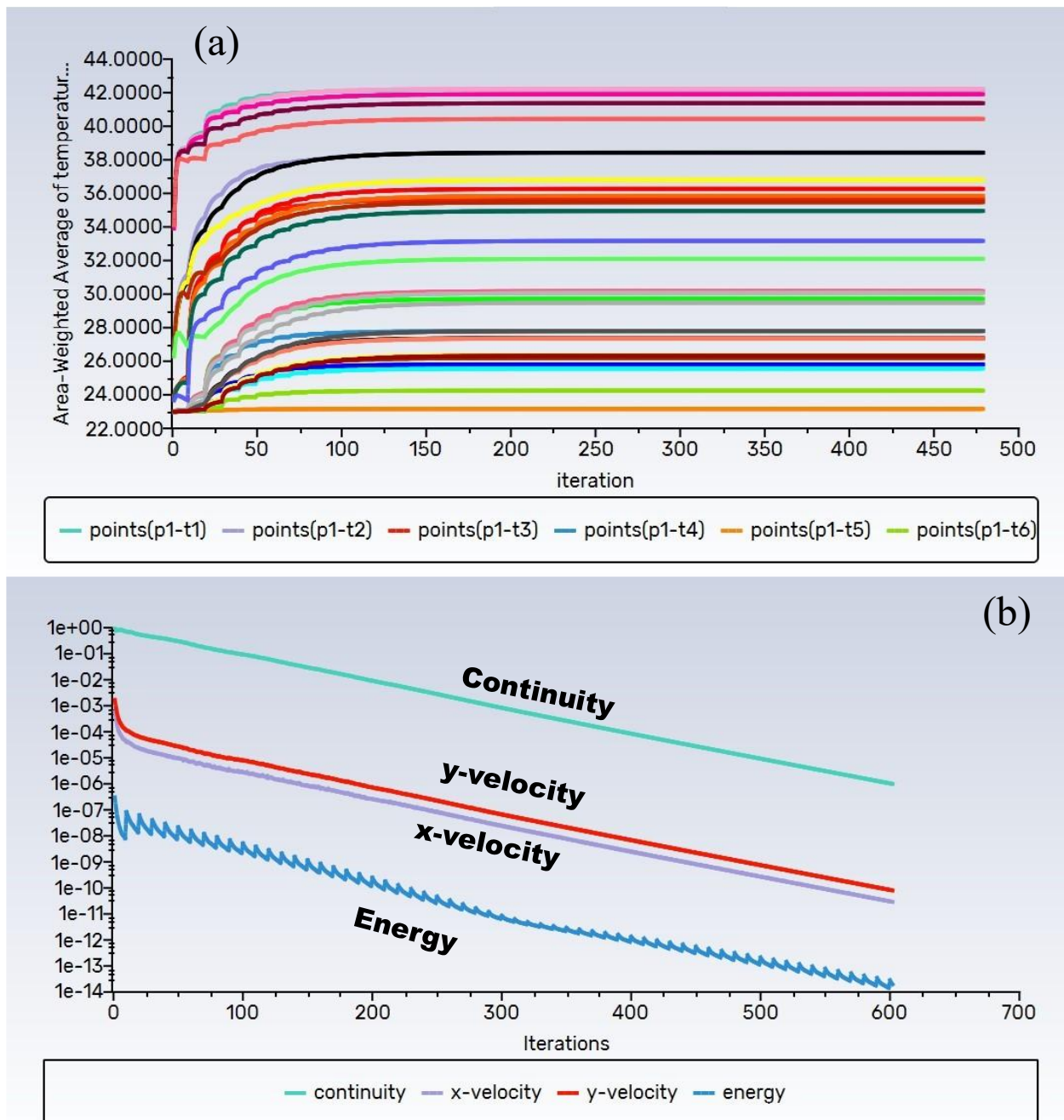


Figure 49. a) Residuals of the measuring points taken across/along EAW systems, b) Residuals of governing equations used in CFD simulations

4.13 Comparative analysis of energy consumption for EAW and conventional glazing systems

The energy performance, as shown in Figure 50, highlights the clear advantage of the EAW best-case configuration over conventional glazing systems and the EAW base model. Across the 12 recorded data points, the EAW best case consistently consumes the least cooling energy, ranging from 58.2670 kWh/m² to 211.2505 kWh/m², depending on seasonal variations or operating conditions. In comparison, the EAW_o ranges from 65.3811 kWh/m² to 220.2224 kWh/m², triple-glazed systems from 76.5381 kWh/m² to 252.2066 kWh/m², and double-glazed systems from 84.4351 kWh/m² to 273.7349 kWh/m². The lowest consumption observed in the EAW_b (58.2670 kWh/m²) is over 700 kWh/m² lower than the EAW base case (65.3811 kWh/m²) for the same condition and over 2600 kWh/m² lower than the double-glazed system (84.4351 kWh/m²).

Averaging all values for each system reveals that the EAW_b has an average cooling energy consumption of approximately 144.18 kWh/m². The EAW_o averages around 151.44 kWh/m², the triple-glazed system about 174.55 kWh/m², and the double-glazed system the highest at around 191.94 kWh/m². When comparing these averages, the EAW best case achieves ~5% energy savings compared to the EAW base case, ~18% savings over the triple-glazed system, and ~25% savings relative to the double-glazed system. These reductions are primarily due to the enhanced heat extraction mechanism of the best-case EAW design, which integrates square bars at 0.05 m c/c. This configuration promotes efficient air circulation and convective heat removal, thereby maintaining cooler inner

glazing temperatures and reducing the burden on HVAC systems. In contrast, conventional systems rely mainly on passive insulation, which, while effective to an extent, cannot match the active thermal regulation offered by the EAW design. This analysis underscores the EAW_b's superior energy performance and practical viability as an innovative solution for reducing building cooling demands.

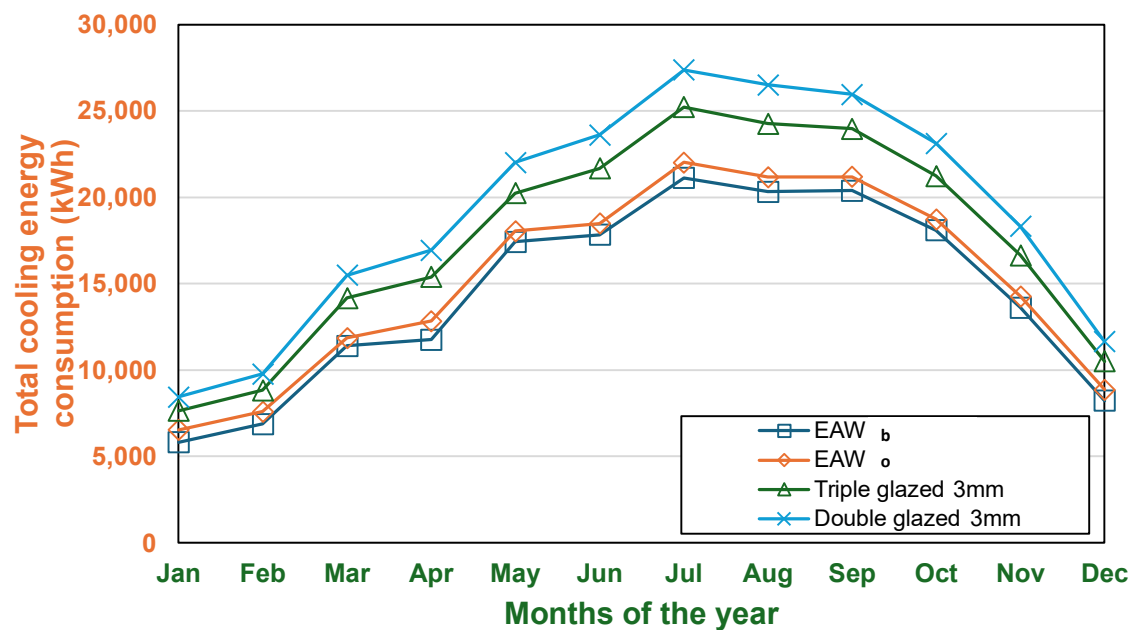


Figure 50. Comparison of total cooling energy consumption (kWh) among EAW_{b-3}, EAW_o, and conventional triple- and double-glazed systems

4.14 Comparative analysis of thermal comfort for EAW and conventional glazing systems

The given Table (Appendix B) presents the monthly thermal comfort performance of different glazing systems, specifically, the Energy-Active Window (EAW) best case, EAW

base case, and conventional double and triple glazing—assessed using the Fanger Predicted Mean Vote (PMV) index. The PMV, as shown in Figure 51, indicates how occupants perceive thermal conditions, with values closer to 0 representing thermal neutrality and comfort, while values above +1 or below -1 suggest increasing discomfort due to heat or cold, respectively.

The EAW best case consistently outperforms all other configurations by maintaining PMV values closer to zero throughout the year. For instance, in January, it shows a PMV of -0.68, which is significantly better than the EAW base case (-1.00), double glazing (-1.23), and triple glazing (-1.18), indicating improved indoor warmth and reduced discomfort during cold months. This comfort advantage remains evident in February and March, where the best-case records are -0.41 and -0.39, compared to more negative values in conventional setups.

In warmer months like June to August, where overheating is a concern, the EAW best case still maintains reasonable PMV values, such as 0.42 in June and 0.98 in August, compared to 0.67 and 1.22 in the double-glazing setup, which suggests excessive warmth. Importantly, the EAW best case avoids crossing the critical PMV threshold of +1 (slightly warm), which both double and triple glazing do in July and August.

During the transitional months (April, September, and October), the EAW best case stays very close to thermal neutrality. For example, it scored -0.04 in April, essentially a neutral condition, outperforming all other cases. Even in November and December, the EAW best case offers improved comfort with -0.19 and -0.51, as opposed to the more discomforting -0.32 and -0.77 seen in the base case.

The EAW best case demonstrates enhanced thermal comfort year-round, minimizing cold discomfort in winter and overheating in summer. This balanced PMV performance signifies that integrating optimized square bar configurations improves energy performance and creates a more comfortable indoor environment than both traditional EAW setups and conventional double/triple glazing systems.

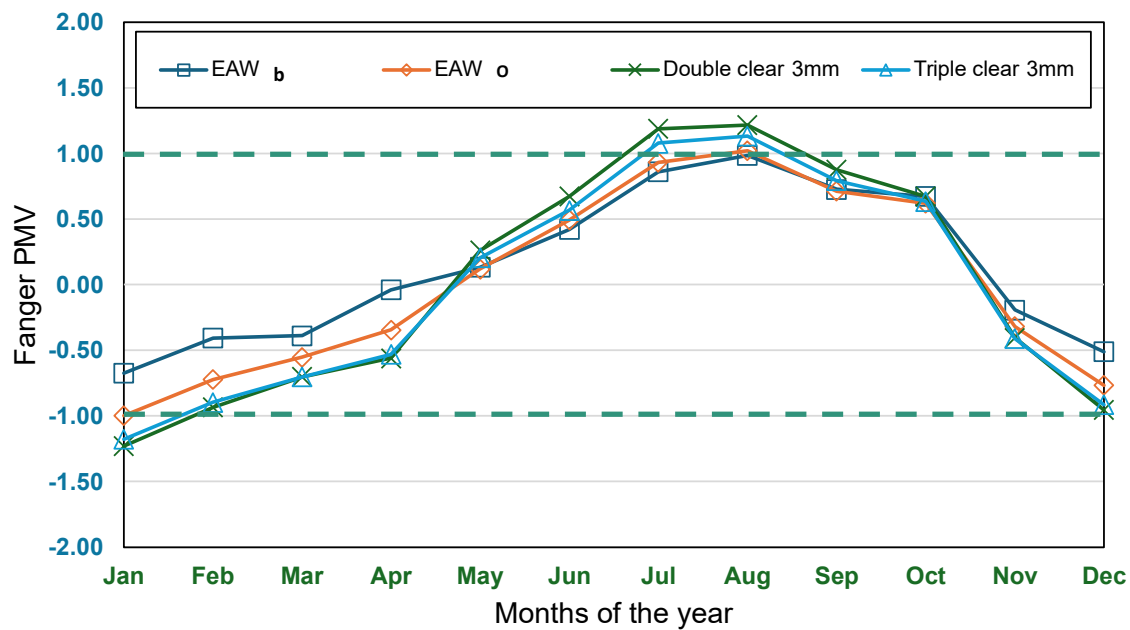


Figure 51. Comparison of thermal comfort (PMV) among EAW_{b-3}, EAW_o, and conventional triple- and double-glazed systems

CHAPTER 5

CONCLUSION & RECOMMENDATIONS

5.1 Conclusions

This study investigated the thermal performance, energy efficiency, and indoor comfort potential of an advanced Energy-Active Window (EAW) system integrated with internal airflow channels and polycarbonate aerodynamic elements of varying shapes and configurations. The study began with the validation of conventional glazing types (single, double, and triple clear glass) using EnergyPlus, where simulated results for cooling electricity consumption were found to be within a margin of $\pm 5\%$ compared to existing literature, confirming the reliability of the simulation approach. Following this, a baseline EAW system (without internal airflow bars) was developed and simulated under steady-state CFD conditions to assess temperature distributions across the window height and cross-section at varying airflow velocities.

The base case analysis revealed that lower velocities (0.24 m/s) resulted in higher outflow temperatures ($T_{\text{out}} = 38.81^{\circ}\text{C}$) due to extended residence time, allowing greater heat absorption from the outer glazing. As the velocity increased to 0.57 m/s, the outflow decreased to 35.36°C , confirming the inverse relation between airflow speed and heat retention. The average value of pane temperature difference (ΔT_{avg}) also showed a gradual

decline from 15.97°C at 0.24 m/s to 15.73°C at 0.57 m/s, emphasizing the importance of controlled air movement in optimizing thermal exchange.

To enhance performance, various aerodynamic bar shapes: circular, square, and triangular were integrated into the EAW system, placed at specific intervals (0.1 m) within the inflow and outflow air slots. Among the alternatives, square bars demonstrated superior results, especially Alternative 2 (SA2), where three square bars were positioned at 0.1 m center-to-center (c/c) in the outflow air slot only. This configuration recorded the highest RAT (39.04°C) and the greatest ΔT (16.06°C), outperforming all other configurations, including the base case. The effectiveness of SA2 was consistent across different airflow velocities and inflow/outdoor temperature scenarios, where it continued to show improved heat uptake, better convective transfer, and stable glazing temperatures.

Further refinement was conducted by studying bar spacing, comparing configurations at 0.05 m, 0.1 m, and 0.2 m c/c. The case with tighter spacing (0.05 m), although resulting in a slightly lower inner glazing temperature (23.3°C) due to enhanced airflow disruption, provided the highest outflow-inflow temperature difference of 16.45°C, indicating maximum heat exchange efficiency. However, the balance between airflow disturbance and effective heat absorption confirmed that Alternative 2 (0.1 m spacing) remains the optimal design in terms of both performance and practicality.

From an energy perspective, simulations in EnergyPlus showed that the EAW best case consumed significantly less cooling energy compared to both conventional glazing and the EAW base case. Specifically, the total annual cooling load for the EAW best case was approximately 132,370.8 kWh, compared to 144,398.7 kWh for the EAW base case,

165,167.8 kWh for triple glazing, and 180,330.4 kWh for double glazing. This reflects a ~8.35% energy savings compared to the base case and up to ~26.6% savings compared to double-glazed systems.

Thermal comfort analysis using the Fanger PMV index further reinforced the benefits of the EAW best case. Throughout the year, it consistently provided PMV values closer to thermal neutrality, ranging from -0.68 in January to 0.98 in August, thus maintaining thermal comfort within the acceptable range of -1 to +1. In contrast, conventional glazing types often exceeded these bounds during extreme months, indicating excessive cold or heat exposure indoors.

Finally, the U-value analysis highlighted a striking contrast: while conventional single, double, and triple glazing exhibited U-values of 5.8, 3.16, and 2.2 W/m²K respectively, the EAW base case achieved a U-value of 1 W/m²K, and the best case (SA2 with 0.05 m spacing) demonstrated an exceptionally low U-value of 0.12 W/m²K, confirming substantial improvement in insulating capabilities and reduction in heat loss.

In summary, integrating square aerodynamic bars in the outflow slot of the EAW system significantly enhances the thermal, energy, and comfort performance of window systems. The best-performing configuration (SA2) increases the outflow temperature for potential recovery, reduces energy demand, and maintains better indoor conditions year-round. These findings strongly advocate for adopting airflow-assisted window systems as a viable passive strategy in building energy optimization and sustainable design.

5.2 Recommendations

The findings of this study clearly demonstrate the substantial potential of Energy-Active Window (EAW) systems integrated with internal airflow mechanisms for enhanced thermal management. Particularly, the implementation of aerodynamic square bars strategically positioned within the outflow air slot at intervals between 0.05 and 0.1 meters significantly improved thermal performance, achieving optimal air return temperatures (up to 39.45°C) and notable energy savings of approximately 26.6% relative to conventional double-glazed systems. This configuration facilitates enhanced convective heat transfer, superior thermal comfort (PMV ranging from -0.68 to 0.98), and exceptionally low thermal transmittance (U-values down to 0.12 W/m²K).

It is strongly advised that future implementations maintain airflow velocities close to 0.24 m/s to maximize heat transfer efficiency through increased air residence time. Such controlled velocities yield higher energy recovery and improved indoor thermal comfort without significantly increasing pressure drops or causing discomfort.

Policy guidelines for adopting and installing EAW systems should mandate adherence to optimized aerodynamic configurations validated by this study, ensuring consistent performance across different building typologies. Regulatory frameworks should encourage the integration of EAW systems into building codes, specifically targeting regions with substantial cooling demands, thereby directly contributing to national energy-saving targets.

For future research, several practical recommendations are outlined. Firstly, beyond the examined circular, square, and triangular bar geometries, researchers should investigate alternative bar configurations and spatial arrangements to further optimize airflow behavior and thermal efficiency. Secondly, integrating dynamic and adaptive components managed by an AI-driven operational system could significantly enhance real-time responsiveness to environmental variations, thus improving the EAW system's adaptability and performance. Thirdly, adding an integrated air curtain system or incorporating concave or convex vortex generators could further refine thermal management through enhanced controlled airflow patterns, subsequently boosting heat transfer effectiveness. Fourthly, a controlled turbulence mechanism is recommended to elevate convective heat transfer without substantially increasing pressure losses or system complexity.

Furthermore, incorporating photovoltaic glazing (PV glazing) engineered for forced convection, powered by renewable energy sources such as solar-driven fan systems, represents an innovative pathway to sustainability. This hybrid approach contributes to energy efficiency and supports overall building energy autonomy. Additionally, comprehensive experimental validation through prototyping and wind tunnel testing is necessary to reinforce computational findings, improve predictive accuracy, and expedite commercialization. Long-term durability assessments under diverse climatic stressors will ensure EAW systems' practical viability and robustness in various environmental conditions. Ultimately, adopting these strategic guidelines and practical recommendations will foster the development of highly efficient, adaptive, and sustainable Energy-Active Window systems, significantly contributing to global energy conservation efforts and advancing sustainable architectural practices.

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Appendix A

Table 19. Temperature of measuring points along window height and cross-section for EAW base case

			OF Slot			IF Slot				
Temperature along window height	Tout	T1	T2	T3	T4	T5	T6	Tin	Window Height (m)	ΔT
P1	45	42.28	38.63	35.7	27.82	23.21	24.26	23	0.05	18.02
P2	45	42.27	38.33	36.12	29.58	25.4	25.47	23	0.25	16.8
P3	45	41.98	36.86	35.85	30.18	26.74	26.13	23	0.45	15.85
P4	45	41.47	34.92	34.93	30.21	27.61	26.41	23	0.65	15.06
P5	45	40.45	31.1	33.15	29.63	28.1	26.36	23	0.85	14.09
Velocity = 0.24 m/s									Avg. of pane temp.	15.964
Outflow temperature = 38.8 °C										
			OF Slot			IF Slot				
Temperature along window height	Tout	T1	T2	T3	T4	T5	T6	Tin	Window Height (m)	ΔT
P1	45	41.92	37.31	34.96	27.24	23.08	24.05	23	0.05	17.87
P2	45	41.81	36.64	35.12	28.77	24.62	25.01	23	0.25	16.8
P3	45	41.42	34.83	34.63	29.18	25.7	25.51	23	0.45	15.91
P4	45	40.87	32.79	33.64	29.15	26.5	25.76	23	0.65	15.11
P5	45	39.89	29.34	32.1	28.71	27.06	25.78	23	0.85	14.11
Velocity = 0.33 m/s									Avg. of pane temp.	15.960
Return Air Temp = 37.86 °C										
			OF Slot			IF Slot				
Temperature along window height	Tout	T1	T2	T3	T4	T5	T6	Tin	Window Height (m)	ΔT

P1	45	41.6	36.11	34.32	26.86	23.04	23.91	23	0.05	17.69
P2	45	41.43	35.26	34.33	28.23	24.18	24.73	23	0.25	16.7
P3	45	41	33.31	33.74	28.51	25.07	25.12	23	0.45	15.88
P4	45	40.45	31.3	32.76	28.45	25.78	25.33	23	0.65	15.12
P5	45	39.51	28.21	31.38	28.08	26.34	25.38	23	0.85	14.13
Velocity = 0.41 m/s									Avg. of pane temp.	15.904
Return Air Temp = 37.10 °C										
			OF Slot			IF Slot				
Temperature along window height	Tout	T1	T2	T3	T4	T5	T6	Tin	Window Height (m)	
P1	45	41.3	34.98	33.72	26.52	23	23.8	23	0.05	17.5
P2	45	41.1	34.03	33.64	27.78	23.88	24.53	23	0.25	16.57
P3	45	40.65	32.02	33.01	27.98	24.62	24.84	23	0.45	15.81
P4	45	40.11	30.11	32.07	27.91	25.26	25.02	23	0.65	15.09
P5	45	39.2	27.37	30.84	27.6	25.79	25.07	23	0.85	14.13
Velocity = 0.49 m/s									Avg. of pane temp.	15.82
Return Air Temp = 36.45 °C										
			OF Slot			IF Slot				
Temperature along window height	Tout	T1	T2	T3	T4	T5	T6	Tin	Window Height (m)	
P1	45	41.03	33.94	33.19	26.23	23	23.71	23	0.05	17.32
P2	45	40.81	32.96	33.05	27.41	23.67	24.37	23	0.25	16.44
P3	45	40.35	30.95	32.41	27.58	24.29	24.63	23	0.45	15.72
P4	45	39.83	29.15	31.53	27.5	24.86	24.78	23	0.65	15.05
P5	45	38.95	26.73	30.41	27.22	25.37	24.83	23	0.85	14.12
Velocity = 0.57 m/sec									Avg. of pane temp.	15.73
Return Air Temp = 35.36 C										

Table 20. Temperature of measuring points along window height and cross-section for EAW with integrated circular bars

Circular bars	Alternative 1	Outflow temperature = 38.78 °C							
Temperature distribution	T _{out}	T1	T2	T3	T4	T5	T6	T _{in}	ΔT
P1	45	42.29	38.86	35.79	27.42	23.15	24.21	23	18.08
P2	45	42.27	38.1	36.18	29.33	25.64	25.42	23	16.85
P3	45	42.02	36.92	35.9	30.1	27.2	26.15	23	15.87
P4	45	41.49	34.98	34.93	30.21	28	26.48	23	15.01
P5	45	40.43	31.2	33.04	29.71	28.12	26.45	23	13.98
Velocity = 0.24 m/s			OF			IF			15.958
Circular bars	Alternative 2	Outflow temperature = 39 °C							
Temperature distribution	T _{out}	T1	T2	T3	T4	T5	T6	T _{in}	ΔT
P1	45	42.39	38.87	35.77	27.85	23.15	24.27	23	18.12
P2	45	42.38	38.46	36.23	29.62	25.43	25.49	23	16.89
P3	45	42.14	37.71	35.96	30.22	26.94	26.13	23	16.01
P4	45	41.55	35.53	34.95	30.2	27.79	26.41	23	15.14
P5	45	40.35	31.1	32.89	29.45	28.07	26.3	23	14.05
Velocity = 0.24 m/s			OF			IF			16.042
Circular bars	Alternative 3	Outflow temperature = 38.96 °C							
Temperature distribution	T _{out}	T1	T2	T3	T4	T5	T6	T _{in}	ΔT
P1	45	42.38	39.15	35.72	27.79	23.15	24.22	23	18.16
P2	45	42.3	38.49	36.21	29.61	26.66	25.44	23	16.86
P3	45	42.14	37.74	35.99	30.31	27.03	26.17	23	15.97
P4	45	41.58	35.59	35.03	30.32	28.03	26.48	23	15.1

P5	45	40.4	31.25	32.97	29.59	28.08	26.38	23	14.02
Velocity = 0.24 m/s			OF			IF			16.022
Circular bars	Alternative 4	Outflow temperature = 38.82 °C							
Temperature distribution	Tout	T1	T2	T3	T4	T5	T6	Tin	ΔT
P1	45	42.31	38.89	35.72	27.82	23.21	24.25	23	18.06
P2	45	42.27	38.32	36.14	29.59	25.5	25.52	23	16.75
P3	45	41.97	36.85	35.84	30.15	26.81	26.16	23	15.81
P4	45	41.42	34.9	34.91	30.15	27.75	26.42	23	15
P5	45	40.38	30.79	33.11	29.55	27.92	26.36	23	14.02
Velocity = 0.24 m/s			OF			IF			15.928
Circular bars	Alternative 5	Outflow temperature = 38.76 °C							
Temperature distribution	Tout	T1	T2	T3	T4	T5	T6	Tin	ΔT
P1	45	42.22	38.8	35.7	27.8	23.15	24.25	23	17.97
P2	45	42.18	38	36.11	29.55	25.23	25.44	23	16.74
P3	45	41.92	37.09	35.85	30.16	26.89	26.1	23	15.82
P4	45	41.38	34.73	34.99	30.21	27.6	26.42	23	14.96
P5	45	40.44	31.5	33.25	29.65	28.09	26.38	23	14.06
Velocity = 0.24 m/s			OF			IF			15.91
Circular bars	Alternative 6	Outflow temperature = 38.78 °C							
Temperature distribution	Tout	T1	T2	T3	T4	T5	T6	Tin	ΔT
P1	45	42.22	38.8	35.72	27.82	23.21	24.25	23	17.97
P2	45	42.19	38.04	36.14	29.57	25.49	25.51	23	16.68
P3	45	41.92	36.86	35.86	30.14	26.78	26.15	23	15.77

P4	45	41.38	34.94	34.97	30.16	27.76	26.42	23	14.96
P5	45	40.43	31.47	33.22	29.58	27.91	26.38	23	14.05
Velocity = 0.24 m/s			OF			IF			15.886

Table 21. Temperature of measuring points along window height and cross-section for EAW with integrated square bars

Square bars	Alternative 1	Outflow temperature = 38.77 °C							
Temperature distribution	Tout	T1	T2	T3	T4	T5	T6	Tin	ΔT
P1	45	42.29	38.85	35.62	27.74	23.15	24.21	23	18.08
P2	45	42.27	38.1	36.1	29.54	25.53	25.4	23	16.87
P3	45	42	37.17	35.88	30.27	27.26	26.15	23	15.85
P4	45	41.5	34.73	35.01	30.34	28.1	26.48	23	15.02
P5	45	40.49	30.93	33.26	29.78	28.32	26.45	23	14.04
Velocity = 0.24 m/s									15.972
Square bars	Alternative 2	Outflow temperature = 39.04 °C							
Temperature distribution	Tout	T1	T2	T3	T4	T5	T6	Tin	ΔT
P1	45	42.41	38.94	35.82	27.85	23.16	24.27	23	18.14
P2	45	42.4	38.86	36.29	29.66	25.44	25.5	23	16.9
P3	45	42.16	38.8	36.04	30.27	26.79	26.15	23	16.01
P4	45	41.58	35.72	35.01	30.24	27.66	26.43	23	15.15
P5	45	40.41	31.67	32.85	29.44	28.09	26.3	23	14.11
Velocity = 0.24 m/s									16.062
Square bars	Alternative 3	Outflow temperature = 39 °C							

Temperature distribution	Tout	T1	T2	T3	T4	T5	T6	Tin	ΔT
P1	45	42.39	39.17	35.74	27.79	23.21	24.22	23	18.17
P2	45	42.4	38.89	36.25	29.62	25.55	25.44	23	16.96
P3	45	42.14	37.87	36.06	30.35	27.32	26.19	23	15.95
P4	45	41.61	35.77	35.08	30.37	28.14	26.53	23	15.08
P5	45	40.44	31.75	32.96	29.59	28.14	26.41	23	14.03
Velocity = 0.24 m/s									16.038
Square bars	Alternative 4	Outflow temperature = 38.80 °C							
Temperature distribution	Tout	T1	T2	T3	T4	T5	T6	Tin	ΔT
P1	45	42.3	38.87	35.68	27.8	23.15	24.25	23	18.05
P2	45	42.27	38.31	36.09	29.46	25.21	25.51	23	16.76
P3	45	41.96	37.09	35.8	30.01	26.71	26.14	23	15.82
P4	45	41.45	34.87	34.9	30.18	27.96	26.48	23	14.97
P5	45	40.38	31.04	33.08	29.56	28.2	26.42	23	13.96
Velocity = 0.24 m/s									15.912
Square bars	Alternative 5	Outflow temperature = 38.68 °C							
Temperature distribution	Tout	T1	T2	T3	T4	T5	T6	Tin	ΔT
P1	45	42.24	38.91	35.78	27.84	23.15	24.26	23	17.98
P2	45	42.14	37.67	36.08	29.56	25.42	25.46	23	16.68
P3	45	41.94	37.26	35.92	30.19	26.74	26.12	23	15.82
P4	45	41.33	34.51	34.98	30.22	27.62	26.41	23	14.92
P5	45	40.44	32.09	33.22	29.64	27.96	26.38	23	14.06
Velocity = 0.24 m/s									15.892

Square bars	Alternative 6	Outflow temperature = 38.81 °C							
Temperature distribution	Tout	T1	T2	T3	T4	T5	T6	Tin	ΔT
P1	45	42.18	38.41	35.66	27.8	23.15	24.25	23	17.93
P2	45	42.23	38.43	36.26	29.72	25.81	25.56	23	16.67
P3	45	41.91	36.8	35.85	30.17	27.37	26.2	23	15.71
P4	45	41.37	35.47	34.95	30.06	27.35	26.39	23	14.98
P5	45	40.43	32.1	33.16	29.48	27.8	26.33	23	14.1
Velocity = 0.24 m/s									15.878

Table 22. Temperature of measuring points along window height and cross-section for EAW with integrated square bars

Triangular bars	Alternative 1	Outflow temperature = 38.79 °C							
Temperature distribution	Tout	T1	T2	T3	T4	T5	T6	Tin	ΔT
P1	45	42.29	38.63	35.77	27.48	23.2	24.22	23	18.07
P2	45	42.26	38.32	36.17	29.38	25.64	25.43	23	16.83
P3	45	42	37.13	35.9	30.12	27.17	26.14	23	15.86
P4	45	41.48	34.96	34.95	30.24	27.88	26.49	23	14.99
P5	45	40.47	30.94	33.07	29.7	28.25	26.44	23	14.03
Velocity = 0.24 m/s									15.956
Triangular bars	Alternative 2	Outflow temperature = 38.98 °C							
Temperature distribution	Tout	T1	T2	T3	T4	T5	T6	Tin	ΔT
P1	45	42.38	39.12	35.91	27.56	23.2	24.27	23	18.11
P2	45	42.34	38.72	36.32	29.43	25.27	25.48	23	16.86
P3	45	42.1	37.45	36	30.08	26.78	26.14	23	15.96

P4	45	41.53	35.58	34.96	30.12	27.78	26.42	23	15.11
P5	45	40.42	31.27	32.78	29.44	28.07	26.32	23	14.10
Velocity = 0.24 m/s									16.028
Triangular bars	Alternative 3	Outflow temperature = 38.95 °C							
Temperature distribution	Tout	T1	T2	T3	T4	T5	T6	Tin	ΔT
P1	45	42.37	39.12	35.86	27.51	23.2	24.23	23	18.14
P2	45	42.34	38.74	36.3	29.44	25.52	25.45	23	16.89
P3	45	42.1	37.46	36	30.17	27.2	26.18	23	15.92
P4	45	41.54	35.6	35	30.22	27.87	26.48	23	15.06
P5	45	40.45	31.61	32.86	29.55	28.1	26.39	23	14.06
Velocity = 0.24 m/s									16.014
Triangular bars	Alternative 4	Outflow temperature = 38.82 °C							
Temperature distribution	Tout	T1	T2	T3	T4	T5	T6	Tin	ΔT
P1	45	42.31	38.89	35.87	27.82	23.16	24.26	23	18.05
P2	45	42.27	38.32	36.22	29.61	25.35	25.53	23	16.74
P3	45	42	36.84	35.85	30.17	26.95	26.14	23	15.86
P4	45	41.46	34.61	34.84	30.17	27.77	26.43	23	15.03
P5	45	40.43	30.77	32.89	29.55	27.91	26.36	23	14.07
Velocity = 0.24 m/s									15.95
Triangular bars	Alternative 5	Outflow temperature = 38.76 °C							
Temperature distribution	Tout	T1	T2	T3	T4	T5	T6	Tin	ΔT
P1	45	42.23	38.82	35.85	27.45	23.2	24.26	23	17.97
P2	45	42.23	38.07	36.21	29.31	25.23	25.45	23	16.78

P3	45	41.96	36.85	35.87	29.97	26.89	26.1	23	15.86
P4	45	41.39	34.98	34.92	30.07	27.59	26.4	23	14.99
P5	45	40.48	31.38	33.05	29.58	27.95	26.36	23	14.12
Velocity = 0.24 m/s									15.944
Triangular bars	Alternative 6	Outflow temperature = 38.78 °C							
Temperature distribution	Tout	T1	T2	T3	T4	T5	T6	Tin	ΔT
P1	45	42.23	38.84	35.88	27.47	23.21	24.26	23	17.97
P2	45	42.23	38.28	36.23	29.36	25.52	25.52	23	16.71
P3	45	41.96	37.08	35.88	29.96	26.94	26.13	23	15.83
P4	45	41.43	34.71	34.9	30.03	27.6	26.42	23	15.01
P5	45	40.47	31.36	33.02	29.51	27.93	26.37	23	14.10
Velocity = 0.24 m/s									15.924

Table 23. Outflow-inflow and average of pane temperature difference for various configurations integrated in EAW system

		Outflow Temperature	Inflow Temp (Tif)	ΔT (Tof-Tif)
Circular	CA1	38.78	23.00	15.78
	CA2	39.00	23.00	16.00
	CA3	38.96	23.00	15.96
	CA4	38.82	23.00	15.82
	CA5	38.76	23.00	15.76
	CA6	38.78	23.00	15.78
Square	SA1	38.77	23.00	15.77
	SA2	39.04	23.00	16.04

	SA3	39.00	23.00	16.00
	SA4	38.80	23.00	15.80
	SA5	38.68	23.00	15.68
	SA6	38.81	23.00	15.81
Triangular	TA1	38.79	23.00	15.79
	TA2	38.98	23.00	15.98
	TA3	38.95	23.00	15.95
	TA4	38.82	23.00	15.82
	TA5	38.76	23.00	15.76
	TA6	38.78	23.00	15.78
		Average of pane temperature difference ΔT_{avg}		
Circular	A1	15.96		
	A2	16.04		
	A3	16.02		
	A4	15.93		
	A5	15.91		
	A6	15.89		
Square	A1	15.97		
	A2	16.06		
	A3	16.04		
	A4	15.91		
	A5	15.89		
	A6	15.88		
Triangular	A1	15.96		
	A2	16.03		
	A3	16.01		

	A4	15.95		
	A5	15.94	Base Case	Base Case
	A6	15.92	38.8	15.9

Table 24. Thermal performance of EAW system with integrated square bars (best-case, SA2) at various velocities

Square bars (Best Case)	Alternative = 2	Velocity = 0.24m/s								
Temperature distribution	Tout	T1	T2	T3	T4	T5	T6	Tin	ΔT	RAT
P1	45	42.41	38.94	35.82	27.85	23.16	24.27	23	18.14	39.04
P2	45	42.4	38.86	36.29	29.66	25.44	25.5	23	16.9	
P3	45	42.16	38.8	36.04	30.27	26.79	26.15	23	16.01	
P4	45	41.58	35.72	35.01	30.24	27.66	26.43	23	15.15	
P5	45	40.41	31.67	32.85	29.44	28.09	26.3	23	14.11	
									16.062	
Square bars (Best Case)	Alternative = 2	Velocity = 0.33m/s								
Temperature distribution	Tout	T1	T2	T3	T4	T5	T6	Tin	ΔT	RAT
P1	45	42.09	37.87	35.2	27.35	23.05	24.07	23	18.02	38.31
P2	45	41.95	37.38	35.34	28.88	24.65	25.04	23	16.91	
P3	45	41.59	36.3	34.85	29.26	25.74	25.53	23	16.06	
P4	45	40.92	33.74	33.66	29.13	26.54	25.76	23	15.16	
P5	45	39.78	30.07	31.71	28.47	27.04	25.7	23	14.08	
									16.046	
Square bars (Best Case)	Alternative = 2	Velocity = 0.41m/s								
Temperature distribution	Tout	T1	T2	T3	T4	T5	T6	Tin	ΔT	RAT
P1	45	41.8	36.68	34.63	26.97	23.02	23.94	23	17.86	37.62

P2	45	41.59	36.01	34.61	28.34	24.21	24.77	23	16.82	
P3	45	41.22	35.79	33.97	28.58	25.11	25.15	23	16.07	
P4	45	40.48	31.97	32.75	28.41	25.82	25.33	23	15.15	
P5	45	39.38	29.44	30.96	27.82	26.33	25.3	23	14.08	
									15.996	
Square bars (Best Case)	Alternative = 2	Velocity = 0.49m/s								
Temperature distribution	Tout	T1	T2	T3	T4	T5	T6	Tin	ΔT	RAT
P1	45	41.44	35.35	34.06	26.64	23.01	23.83	23	17.61	36.94
P2	45	41.26	34.68	33.97	27.91	23.91	24.57	23	16.69	
P3	45	40.98	35.62	33.2	28.04	24.66	24.86	23	16.12	
P4	45	40.04	32.7	31.97	27.82	25.29	25	23	15.04	
P5	45	39.24	29.63	30.28	27.29	25.77	24.97	23	14.27	
									15.946	
Square bars (Best Case)	Alternative = 2	Velocity = 0.57m/s								
Temperature distribution	Tout	T1	T2	T3	T4	T5	T6	Tin	ΔT	RAT
P1	45	41.06	34.25	33.56	26.36	23	23.74	23	17.32	36.45
P2	45	40.88	33.48	33.41	27.54	23.69	24.41	23	16.47	
P3	45	40.87	35.74	32.5	27.59	24.33	24.63	23	16.24	
P4	45	39.73	32.65	31.3	27.35	24.88	24.74	23	14.99	
P5	45	39.26	30.27	29.66	26.86	25.34	24.72	23	14.54	
									15.912	

Table 25. Thermal performance of EAW system integrated with square bars (best case, SA2) at various inflow and outdoor temperatures

Square Bars (Velocity = 0.24 m/s)	Alternative = 2		SA = 23C		Tout = 43					
Temperature distribution	Tout	T1	T2	T3	T4	T5	T6	Tin	ΔT	RAT
P1	43	40.66	37.49	34.64	27.4	23.14	24.15	23	16.51	37.58
P2	43	40.65	37.4	35.06	29.03	25.21	25.26	23	15.39	
P3	43	40.43	36.52	34.83	29.58	26.43	25.85	23	14.58	
P4	43	39.9	34.55	33.89	29.54	27.21	26.1	23	13.8	
P5	43	38.83	30.87	31.93	28.82	27.6	25.98	23	12.85	
									14.63	
Square Bars (Velocity = 0.24 m/s)	Alternative = 2		SA = 23C		Tout = 41					
Temperature distribution	Tout	T1	T2	T3	T4	T5	T6	Tin	ΔT	RAT
P1	41	38.9	36.03	33.46	26.93	23.13	24.03	23	14.87	36.12
P2	41	38.89	35.96	33.83	28.4	24.98	25.02	23	13.87	
P3	41	38.7	35.15	33.62	28.89	26.1	25.54	23	13.16	
P4	41	38.22	33.38	32.77	28.86	26.77	25.77	23	12.45	
P5	41	37.26	30.1	31	28.21	27.12	25.67	23	11.59	
									13.19	
Square Bars (Velocity = 0.24 m/s)	Alternative = 2		SA = 25C		Tout = 45					
Temperature distribution	Tout	T1	T2	T3	T4	T5	T6	Tin	ΔT	RAT
P1	45	42.64	39.48	36.64	29.42	25.14	26.17	25	16.47	39.57
P2	45	42.63	39.41	37.07	31.06	27.23	27.3	25	15.33	
P3	45	42.42	38.53	36.85	31.61	28.46	27.89	25	14.53	
P4	45	41.89	36.57	35.92	31.58	29.25	28.14	25	13.75	
P5	45	40.82	32.9	33.98	30.87	29.64	28	25	12.82	

									14.58	
Square Bars (Velocity = 0.24 m/s)	Alternative = 2		SA = 25C		Tout = 43					
Temperature distribution	Tout	T1	T2	T3	T4	T5	T6	Tin	ΔT	RAT
P1	43	40.88	38.03	35.46	28.96	25.13	26	25	14.88	38.11
P2	43	40.88	37.96	35.84	30.43	26.99	27.05	25	13.83	
P3	43	40.68	37.16	35.64	30.92	28.1	27.58	25	13.1	
P4	43	40.21	35.4	34.8	30.89	28.8	27.8	25	12.41	
P5	43	39.25	32.1	33.05	30.25	29.16	27.7	25	11.55	
									13.15	
Square Bars (Velocity = 0.24 m/s)	Alternative = 2		SA = 25C		Tout = 41					
Temperature distribution	Tout	T1	T2	T3	T4	T5	T6	Tin	ΔT	RAT
P1	41	39.13	36.57	34.28	28.5	25.11	25.93	25	13.2	36.65
P2	41	39.12	36.51	34.62	29.8	26.76	26.81	25	12.31	
P3	41	38.95	35.8	34.44	30.24	27.74	27.28	25	11.67	
P4	41	38.52	34.22	33.68	30.22	28.36	27.48	25	11.04	
P5	41	37.67	31.28	32.12	29.64	28.67	27.39	25	10.28	
									11.70	
Square Bars (Velocity = 0.24 m/s)	Alternative = 2		SA = 19C		Tout = 45					
Temperature distribution	Tout	T1	T2	T3	T4	T5	T6	Tin	ΔT	RAT
P1	45	41.97	37.87	34.21	24.73	19.18	20.46	19	21.51	38
P2	45	41.96	37.75	34.74	26.86	21.87	21.9	19	20.06	
P3	45	41.67	36.59	34.42	27.57	23.45	22.66	19	19.01	
P4	45	40.98	34.01	33.19	27.52	24.47	22.98	19	18	
P5	45	39.59	29.22	30.61	26.57	24.97	22.84	19	16.75	

									19.07	
Square Bars (Velocity = 0.24 m/s)	Alternative = 2		SA = 19C		Tout = 43					
Temperature distribution	Tout	T1	T2	T3	T4	T5	T6	Tin	ΔT	RAT
P1	43	40.21	36.41	33.01	24.26	19.17	20.34	19	19.87	36.53
P2	43	40.24	36.3	33.5	26.22	21.63	21.66	19	18.58	
P3	43	39.93	35.22	33.21	26.87	23.08	22.36	19	17.57	
P4	43	39.3	32.84	32.06	26.82	24.02	22.66	19	16.64	
P5	43	38.01	28.41	29.67	25.95	24.48	22.53	19	15.48	
									17.63	
Square Bars (Velocity = 0.24 m/s)	Alternative = 2		SA = 19C		Tout = 41					
Temperature distribution	Tout	T1	T2	T3	T4	T5	T6	Tin	ΔT	RAT
P1	41	38.46	34.95	31.83	23.8	19.15	20.22	19	18.24	35.06
P2	41	38.45	34.85	32.27	25.6	21.4	21.42	19	17.03	
P3	41	38.2	33.85	32	26.19	22.72	22.06	19	16.14	
P4	41	37.61	31.67	30.94	26.14	23.58	22.33	19	15.28	
P5	41	36.43	27.6	28.74	25.34	24	22.21	19	14.22	
									16.18	

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